PB82-100868

Coal: DRDF (Densified Refuse Derived Fuel) Demonstration Test in an Industrial Spreader Stoker Boiler. Use of Coal: DRDF Blends in Stoker-Fired Boilers. Volume I

Systems Technology Corp.
Xenia, OH

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Sep 81

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/2-81- 183
September 1981

PB82-100868

COAL:dRDF DEMONSTRATION TEST

IN AN INDUSTRIAL SPREADER STOKER BOILER

Use of Coal:dRDF Blends in

Stoker-Fired Boilers

Volume I

by

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EPA Contract Number 68-03-2426

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-81- 183

2.
ORD Report

3. RECIPIENT'S ACCESSION NO.
PB82 10086 8

4. TITLE AND SUBTITLE
Coal: d-RDF Demonstration Test in an Industrial Spreader Stoker Boiler - Volume I.

5. REPORT DATE
September 1981

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Ned J. Kleinhenz

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Systems Technology Corporation
245 North Valley Road
Xenia, Ohio 45385

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-03-2426

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory - Cin., OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer - Carlton C. Wiles 513/684-7871
See also: Volume II
EPA-600/2-81- 184

16. ABSTRACT

This study program has the overall objective of evaluating boiler performance and environmental feasibility when combusting densified forms of refuse derived fuels (dRDF) blended with coal and fired in a modern industrial spreader stoker-fired boiler.

The results reported herein represent the second phase of a two-phase evaluation program. Phase 1 was conducted in an institutional spreader stoker heating boiler. During Phase 1 285 tons of dRDF were combusted. The results of that test are reported in EPA Report No. 600/2-80-095. Phase 2 demonstration testing was conducted in a larger industrial spreader stoker boiler. In a period of 402 hours, 1702 tons of dRDF were co-fired with coal. An additional 231 hours of coal baseline testing was completed to provide a basis of comparison for the test results.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Refuse Evaluation Energy Densification	Municipal Solid Waste Densified Refuse Derived Fuels Resource Recovery	13B

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to preserve and treat public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

In recognition of the fact that more than 50 percent of the roughly 42,000 industrial boilers in the U.S. are coal-fired boilers, the Environmental Protection Agency undertook a project to investigate the technical and environmental implications of using densified (pellet form) refuse derived fuel (dRDF) as a substitute for stoker coal. This report presents the results from co-firing 1702 tons of dRDF when firing at various volumetric blend ratios of coal:dRDF, i.e., 1:1, 1:2, and 1:4.

The investigation specifically addresses the performance of the fuel handling and feeding system, the boiler, and the resulting emissions from each blend firing. Since a spreader stoker-fired (150,000 lb/hr) boiler was co-fired a total of 402 hours without major difficulty, the results are sufficiently encouraging to indicate that co-firing coal and dRDF is a viable alternative to industry.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

ABSTRACT

This study program has the overall objective of evaluating boiler performance and environmental feasibility when combusting densified forms of refuse derived fuels (dRDF) blended with coal and fired in a modern industrial spreader stoker-fired boiler.

The results reported herein represent the second phase of a two-phase evaluation program. Phase 1 was conducted in an institutional spreader stoker heating boiler. During Phase 1 285 tons of dRDF were combusted. The results of that test are reported in EPA Report No. 600/2-80-095. Phase 2 demonstration testing was conducted in a larger industrial spreader stoker boiler. In a period of 402 hours, 1702 tons of dRDF were co-fired with coal. An additional 231 hours of coal baseline testing was completed to provide a basis of comparison for the test results.

The demonstration tests were designed to investigate (1) the material handling characteristics of dRDF after 6 months of storage in an open coal yard; (2) boiler performance, i.e., boiler efficiency, spreader limitations, steam production, combustion properties, slagging, fouling, clinkering, and corrosion; (3) environmental performance, i.e., particulate emissions (size, mass rate, and resistivity), gaseous emissions (SO_x, NO_x, Cl, F, HC), and trace metal emissions (Pb, Cr, Cd, Be, and Zn).

In general, this test clearly demonstrated that co-firing coal and dRDF can be performed with minimal impact on the operational performance of an industrial power plant. The boiler performed well, demonstrating an ability to deliver maximum rated steam capacity with adequate boiler response and fuel burnout at coal:dRDF blends up to 1:4 (by volume). A slight decrease in boiler efficiency (2.5 percent drop) occurred during blend firing. This drop was attributed to the high moisture and hydrogen content of the pellets. There was no significant difference in particulate emissions at either the electrostatic precipitator (ESP) inlet or outlet as a result of firing with blends. ESP collection efficiency was not effected by the blend firing. Increases in heavy metals (namely, lead, cadmium, zinc, chromium) and chloride emissions were noted. Sulfur emissions decreased as the dRDF substitution was increased.

Systems Technology Corporation submitted this report in fulfillment of Contract No. 68-03-2426 sponsored by the Municipal Environmental Research Laboratory of the U.S. Environmental Protection Agency. This report covers the period from January 1, 1978, to July 15, 1980.

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ENGLISH UNITS TO SI UNITS

To convert from	To	Multiply by
in	mm	25.40
in^2	mm^2	645.2
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6$ Btu	ng/J	430
Btu	J	1056
Btu/lb	J/kg	0.002328
Btu/hr	W	0.2929
Btu/ft/hr	W/m	0.9609
Btu/ft/hr	J/h/m	3459
$Btu/ft^2/hr$	W/m^2	3.152
$Btu/ft^2/hr$	$J/h/m^2$	11349
$Btu/ft^3/hr$	W/m^3	10.34
$Btu/ft^3/hr$	$J/h/m^3$	37234
psi	Pa	6895
inches H_2O	Pa	249.1
Rankine	Celsius	C = (5/9R) - 273
Fehrenheit	Celsius	C = 5/9(F - 32)
Celsius	Kelvin	K = C + 273
Rankine	Kelvin	K = 5/9R
mm	in	.03937
mm^2	in^2	.00155
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
kg	lb	2.2056
Mg/s	lb/hr	7.937
ng/J	$lb/10^6$ Btu	0.00233

ENGLISH UNITS TO SI UNITS (continued)

To convert from	To	Multiply by
J	Btu	0.000948
J/kg	Btu/lb	4.303
J/h/m	Btu/ft/hr	0.000289
$J/h/m^2$	$Btu/ft^2/hr$	0.0000881
$J/h/m^3$	$Btu/ft^3/hr$	0.0000269
W	Btu/hr	3.414
W/m	Btu/ft/hr	1.041
W/m^2	$Btu/ft^2/hr$	0.317
W/m^3	$Btu/ft^3/hr$	0.0967
Pa	psi	0.000145
Pa	inches H_2O	0.004014
Kelvin	Fahrenheit	F = 1.8K - 460
Celsius	Fahrenheit	F = 1.8C + 32
Fahrenheit	Rankine	R = F + 460
Kelvin	Rankine	R = 1.8K

ACKNOWLEDGMENT

On behalf of Systems Technology Corporation, the author gratefully acknowledges the direction and cooperation of the EPA Project Officer, Mr. Carlton C. Wiles of the Municipal Environmental Research Laboratory, Cincinnati, Ohio.

The author is also grateful to General Electric Company for providing a host test boiler and to Messrs. James Fitzsimmons and Robert Stinnett of General Electric whose assistance was essential to the successful completion of the program. In addition, special thanks are given to the Technical Advisory Committee consisting of Messrs. Herb Hollander, Robert Sommerlad, Boyd Riley, Roger Hecklinger, and H. Gregor Rigo who provided technical guidance throughout the entire program. Also, the author wishes to acknowledge the contributions of Dr. Al Klee of the EPA Municipal Environmental Research Laboratory for his assistance in carrying out the statistical analysis work.

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SECTION 1

INTRODUCTION

OBJECTIVE

Previous field tests involving co-firing coal and densified refuse derived fuel (dRDF) have typically been of short duration and were performed under less than desirable boiler operating conditions and boiler specifications. Therefore, this demonstration test was proposed with the objective of conducting longer term co-firing tests in a boiler that is representative of those utilized throughout industry. Sufficient testing was to be conducted to establish whether or not dRDF (1) has any detrimental effects on the boiler system or its performance and (2) if it can be burned within existing environmental constraints. The economic considerations of producing dRDF were addressed by the National Center for Resource Recovery, Inc. (NCRR), under Grant No. 804150.

PREVIOUS dRDF TESTING

Since the early 1970's, several short-duration coal:dRDF co-firing test programs have been conducted. Since the majority of these test firings lasted 12 hours or less with only limited data collection, the Environmental Protection Agency (EPA) contracted with Systems Technology Corporation (SYSTECH) to conduct a comprehensive technical and environmental test program. This test program was structured into two separate phases, i.e., Phase 1,A Feasibility Field Test and Phase 2,A Demonstration Test. The Phase 1 Feasibility Test was completed on December 30, 1977, and the results are published as Report No. EPA-600/2-80-095. The feasibility testing was carried out at the Maryland Correctional Institute Power House located in Hagerstown, Maryland. A total of 230 hours of blend firing, consuming 285 tons of pelletized (1/2-in.-diameter by 3/4-in.-long) dRDF, was conducted in two Erie City spreader stoker boilers rated at 60,000 and 75,000 lb/hr, 150 psig saturated steam. These tests provided field data in the areas of fuel handling, boiler performance, and environmental emissions. While the results from these tests indicated that coal and dRDF could be co-fired at volumetric coal:dRDF ratios up to 1:2 with only minor adjustments to the boiler and fuel handling system, the need for further testing was evident. A longer term demonstration test was needed to better establish general boiler performance and the potential for corrosion and fouling. For such demonstration tests, the test facility needed to be an industrial sized boiler (75,000 to 150,000 lb/hr with 200°F superheat steam) with the capability of being operated at various loads up to and including maximum rated capacity. In recognition of these needs, the Phase 2 Demonstration Test was initiated.

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SITE SELECTION

The first requirement of the Demonstration Test was to establish the site selection criteria and then to locate a site. Appendix A presents a detailed discussion of the selection criteria that were established. The basic criteria for selection of a site were:

1. That the site have a spreader stoker boiler with traveling grate (front ash drop) capable of producing 75,000 to 150,000 lb/hr of steam at 500 to 1,000 psig with at least 200°F superheat.
2. That the site have multiple boilers and sufficient steam capacity to permit operating the test boiler at any desired steam load.
3. That the site have adequate fuel storage capacity, a feeding system, and other facilities readily adaptable to testing requirements.
4. The Power Plant management be sufficiently interested and cooperative to ensure successful completion of the program.

Accordingly, approximately 30 to 40 candidate sites were reviewed. These sites were subsequently reduced to 6 through telephone screening. After evaluating these six sites, the General Electric Company Power Plant located in Erie, Pennsylvania, was visited by the technical advisory committee and determined to be the most suitable. This power plant has three Babcock and Wilcox spreader stoker-fired boilers rated at 100,000 lb/hr, 150,000 lb/hr, and 175,000 lb/hr, 825°F and 675 psig superheat steam. The 150,000-lb/hr boiler was selected for the demonstration test. A detailed description of this test boiler and the associated fuel handling system is presented in Section 3.

SUPPLIERS OF dRDF

The EPA contracted the National Center for Resource Recovery (located in Washington, DC) to produce and ship pellets to Erie, Pennsylvania. In order to ensure that an adequate supply of pelletized dRDF was available for the demonstration, Teledyne National (located in Cockeysville, Maryland) was also contracted to supply pellets. Ultimately, 1702 tons of pellets (1256 tons supplied by Teledyne and 446 tons supplied by NCRR) were produced and shipped to Erie. Due to difficulties encountered in the production of the pellets, this quantity was approximately 800 to 1000 tons less than anticipated.

DEMONSTRATION TEST OVERVIEW

The demonstration consisted of four distinct tests; i.e., (1) an initial coal baseline test, (2) co-firing coal and dRDF utilizing the NCRR pellets, (3) co-firing coal and dRDF utilizing the Teledyne pellets, and (4) a final coal baseline test. During the last two tests, a portion of the testing was conducted without fly ash reinjection. Throughout each test, SYSTECH® personnel monitored and evaluated the fuel handling, the boiler performance, and the stack emissions.

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SECTION 2

SUMMARY AND CONCLUSIONS

INTRODUCTION

Over 1,700 tons of densified refuse derived fuel was blended with coal and fired in an industrial spreader stoker boiler. Boiler performance, emissions, and material handling characteristics were monitored during this 402 hour demonstration test. To form a basis of comparison, identical monitoring was performed during an additional 231 hours of coal baseline testing. The results of this demonstration test show that dRDF can be blended with coal and combusted in existing spreader stoker boilers without increasing emissions or significantly decreasing boiler performance. However, some material handling problems were experienced because the pelletized dRDF had deteriorated due to weathering.

FUEL CHARACTERISTICS

Five different coals were used during the blend firing and coal baseline tests. These coals had sulfur contents ranging from 1.7 to 6.8 percent and ash contents ranging from 9.5 to 18.2 percent on a dry weight basis. Two different densified refuse derived fuels were tested. Both dRDF's were formed as 1/2 in. diameter cylindrical pellets. One pellet type, produced by the NCRR, contained over 30 percent ash and had a heating value of 6,755 Btu/lb on a dry weight basis. The other pellet type, produced by Teledyne National, contained 14 percent ash and had a dry weight heating value of 8,123 Btu/lb. Moisture contents of the dRDF ranged from 14 to 34 percent, and bulk densities ranged between 30 and 35 lb/ft^3.

BOILER PERFORMANCE

At a 1:2 (coal:dRDF) volumetric blend ratio, a 2 to 3 percent reduction in boiler efficiency was experienced because of the increased flue gas moisture formed in dRDF combustion. When firing at full load with coal:dRDF blends, the combustion flame was observed to require considerably more combustion volume. Puffs of flame were observed in the screen tube section. This increased flame activity is directly associated with the higher volatile content of dRDF as compared to coal. However, no significant increases in hydrocarbons or carbon monoxide were detected in the flue gas. Uniform flame distribution across the fuel bed was easily achievable when firing both types of dRDF. While NCRR pellets had a tendency to clinker, the lower ash Teledyne pellets did not show this tendency.

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When burning dRDF there was an increase of slag accumulation on the lower furnace walls. However, boiler operators observed that this slag accumulation was easier to remove than coal slag. Small globules of slag were also observed on the screen tubes but did not accumulate. Short term corrosion testing, performed by soaking metal specimens in heated slag samples, indicated that no corrosion problems should be caused by the slag. Fouling was not observed to be a problem during this test. Densified refuse derived fuel caused a 250 percent increase in chloride emissions.

Since the test boiler has proved to be capable of generating steam at 20 percent more than rated capacity, no derating was experienced from the combustion of dRDF. Calculations show that combustion of 100 percent dRDF requires less forced draft fan capacity, 5 percent more induced draft fan capacity, and 3 1/2 times the volumetric fuel feed capacity of coal. Grate speed was increased by about 25 percent when combusting a 1:2 (coal:dRDF) volumetric blend.

MATERIAL HANDLING

The dRDF was stored up to 6 months in an open coal yard through winter and spring weather. The piles of dRDF formed a protective crust 6 to 8 in. thick. While in storage, the pellets increased in moisture and fines content. Also, the aged pellets expanded and formed serrated edges which subsequently created handling problems. While being conveyed to the bunker, the dRDF blended thoroughly with the coal. However, the low bulk density, high elasticity, and fibrous shape of the deteriorating pellets required constant rodding for them to flow out of the conveyor feed hopper. In the bunker, the coal/dRDF blend would "rat hole" and demonstrate angles of repose in excess of 90°. Bunker vibrators and air blasters did not eliminate the need to manually rod the fuel blend into the nonsegregating distribution chutes feeding out of the bunker.

Compared to coal, the dRDF blends required more frequent ash removal because of the increased ash content and decreased heating value of the fuel. Except for the manual removal of the infrequent clinkers, no ash handling problems were noted with the pneumatic ash handling system.

EMISSIONS

The combustion of dRDF blends exhibited the same range of particulate emission rates as coal only. While NCRR blends caused a decrease in particulate size, firing the Teledyne blends resulted in an increase in particulate size when compared to coal only. The electrostatic precipitator performance was unchanged by the substitution of dRDF for coal. However, dRDF raised the fly ash resistivity to 10^8 ohm-cm from the less than 10^7 ohm-cm resistivity of the coal-only fly ash. Lead emissions increased by a factor of six. Cadmium, zinc, and chromium emissions increased 50 to 100 percent when firing dRDF.

The substitution of dRDF for coal had no significant effect on NO_x, CO, or hydrocarbon emissions. But, as expected, dRDF caused a 30 to 50 percent decrease in SO_x emissions.

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Fly ash reinjection from the multiclones was found to have no effect on the mass rate or size distribution of particulate at the ESP inlet when firing dRDF blends. However, fly ash reinjection was found to decrease particulate size when firing coal only.

CONCLUSIONS

It has been demonstrated that coal/dRDF blends can be combusted in an existing spreader stoker boiler at the same excess air levels as coal only. No derating of this boiler was caused by the dRDF substitution, the decrease in boiler efficiency was minimal, and with a low ash dRDF, no operational problems (clinkering) were experienced. There was no measured adverse impact on the emissions from firing dRDF according to existing environmental criteria.

Using existing coal handling equipment, materials handling problems were experienced. Such problems had not been observed in prior tests and may be due only to the aged and weathered condition of the dRDF.

RECOMMENDATIONS

Further study is warranted in the long term (multiyear) corrosion and erosion effects of dRDF combustion.

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SECTION 3

DESCRIPTION OF TESTS, FACILITIES, AND FUELS

The test program was designed to determine the technical and environmental effects of co-firing dRDF and coal in an industrial power plant. To determine these effects, a 150,000 lb/hr steam generator, equipped with a chain grate spreader stoker, was instrumented to monitor efficiency and emissions (see Figure 1).

Two sources for dRDF were secured because dRDF is made in only a few pilot scale plants. Even with dRDF supplying less than half the fuel demand of this industrial boiler, the production of two dRDF plants had to be accumulated for more than 6 months to conduct a demonstration test of 400 hr duration.

TEST DESCRIPTION

A test burn schedule was carried out in March, April, and May of 1979. This schedule was designed to allow the operational and emissions measurements at three boiler loads (45 percent, 75 percent, and maximum) and four volumetric fuel blend ratios (1:0, 1:1, 1:2, and 1:4, coal:dRDF). Tables 1, 2, and 3 show the test burn schedules.

Table 4 shows a typical schedule for any test day. Usually a 4-hr supply of weighed fuel was fed into the bunker shortly after 8 a.m. Steam generation and boiler operation were monitored closely during this 4-hr period. Data collected over this time was used to calculate boiler efficiency. The boiler was then operated at the test load until 5 p.m. Starting at 5 p.m. the boiler was operated at the load to be tested the following day.

The technical effects of dRDF combustion were characterized in terms of boiler efficiency, flue gas characterization, and fireside boiler tube corrosion. Also the effects of dRDF on the operation of the power plant were observed. Material handling was characterized for both fuel and ash.

To characterize the residue, the various fly ash and bottom ash streams were sampled and analyzed. Fly ash reinjection from the multiclone dust collector was terminated in some tests to determine how much it affects fly ash loading within the furnace.

Fuel samples were collected and analyzed during the tests. An accurate characterization of the coals and dRDFs used in the tests was necessary for interpretation of the technical and environmental test results.

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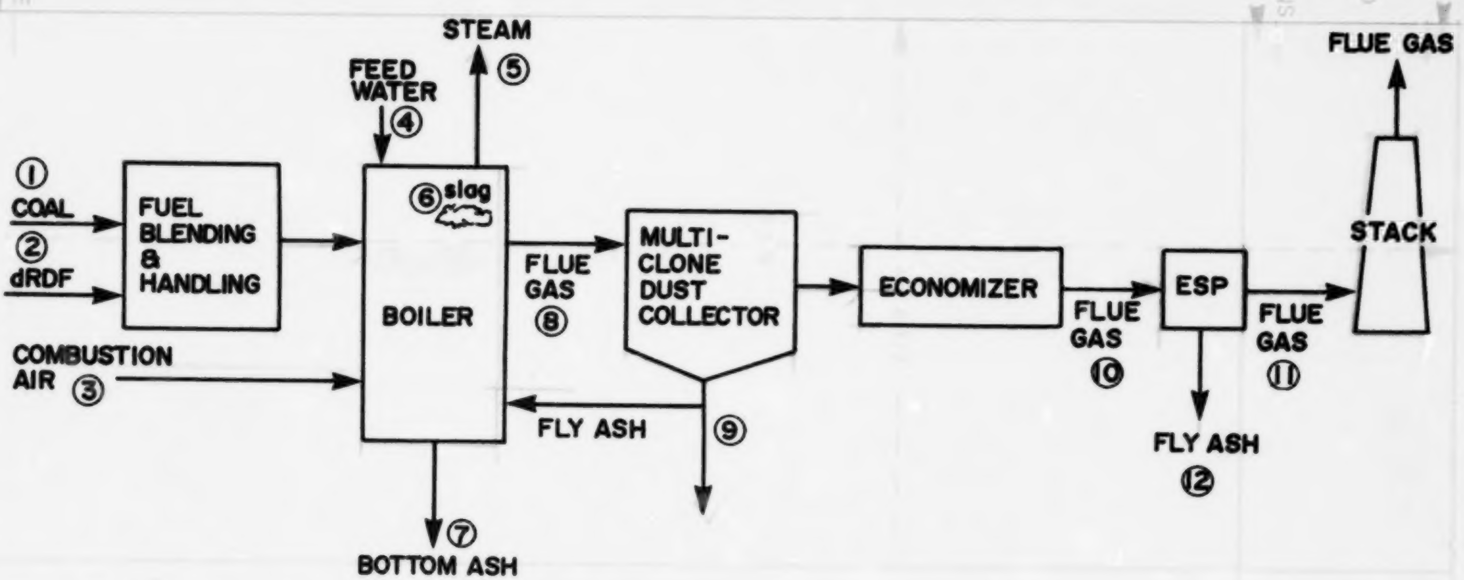
①
COAL
②
dRDF
FUEL BLENDING & HANDLING
COMBUSTION AIR ③
FEED WATER ④
STEAM ⑤
⑥ slag
BOILER
BOTTOM ASH ⑦
FLUE GAS ⑧
FLY ASH
⑨
MULTI-CLONE DUST COLLECTOR
ECONOMIZER
FLUE GAS ⑩
ESP
FLY ASH ⑫
FLUE GAS ⑪
STACK
FLUE GAS

①&②
Weight
Ultimate Analysis
Proximate Analysis
Heating Value
Density
Size

③
Pressures

④&⑤
Temperature
Pressure
Flow Rate

⑥
TGA*
DTA†
SEM§
Ash Chemistry
Corrosivity-
Screening

⑦
Weight
Size
Combustibles
Fusion Temp.
Mineral Analysis

⑧
Particulate
O_2
CO_2
CO
NO_x
SO_2
Temp.
Press.

⑨
Weight
Size
Combustibles

⑩
Particulate
Mass
Size
Resistivity
Metals
Halogens
Temp.

⑪
Particulate
Mass
Size
SO_2
NO_x
Halogens
Temp.
CO
CO_2
O_2
HC

⑫
Size
Combustibles

* Thermal Gravimetric Analysis
† Differential Thermal Analysis
§ Scanning Electron Microscopy

Figure 1. Locations of test measurements.

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TABLE 1. MARCH 1979 SCHEDULE, COAL BASELINE AND NCRR dRDF/COAL TESTS

Date mo/day (1979)	Multiclone fly ash reinjection	Blend volumetric (coal:dRDF)	Boiler demand (%)	Coal type *	dRDF type *
3/5	on	1:0	40	A	-
3/6	on	1:0	40	A	-
3/7	on	1:0	75	A	-
3/8	on	1:0	100	A	-
3/9	on	1:0	100	A	-
3/10			Off line		
3/11			Slag sampling		
3/12	on	1:2	No testing	B	N
3/13	on	1:2	60	B	N
3/14	on	1:2	60	B	N
3/15	on	1:2	75	B	N
3/16	on	1:2	max	B	N
3/17			Off line		
3/18			Slag sampling		

* Fuel types described in Table 12.

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TABLE 2. APRIL 1979 SCHEDULE, TELEDYNE dRDF/COAL TESTS

Date mo/day (1979)	Multiclone fly ash reinjection	Blend volumetric (coal:dRDF)	Boiler demand (%)	Coal type *	dRDF type *
4/18	on	1:2	75	C	T
4/19	on	1:2	80	C	T
4/20	on	1:2	85	C	T
4/21	on	1:1	35	C	T
4/22	on	1:1	No testing	C	T
4/23	on	1:2	100	C	T
4/24	off	1:2	100	C	T
4/25	off	1:2	100	C	T

* Fuel types described in Table 12.

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TABLE 3. MAY 1979 SCHEDULE, COAL BASELINE AND TELEDYNE dRDF/COAL TESTS

Date mo/day (1979)	Multiclone fly ash reinjection	Blend volumetric (coal:dRDF)	Boiler demand (%)	Coal type *	dRDF type *
5/7	on	1:2	40	D	T
5/8	on	1:2	100	D	T
5/9	off	1:2	100	D	T
5/10	on	1:1	100	D	T
5/11	on	1:4	100	D	T
5/12			Off line		
5/13			Slag sampling		
5/14	on	1:0	40	E	-
5/15	on	1:0	70	E	-
5/16	on	1:0	100	E	-
5/17	on	1:0	100	E	-
5/18	off	1:0	100	E	-

* Fuel types described in Table 12.

TABLE 4. DAILY ACTIVITY SCHEDULE

8:00 AM	Fill bunker		
9:00 AM	Start Method 5		Boiler efficiency test period
10:00 AM		Emissions test	
11:00 AM	End Method 5		
12:00 PM	Empty ash Fill bunker		
1:00 PM	Weigh ash, sample ash Start Method 5	Emissions test	
2:00 PM			
3:00 PM			Long boiler efficiency test nonconstant load period
4:00 PM	End Method 5		
5:00			

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Both the particulate and gaseous emissions were analyzed. Particulate emissions were characterized for mass rate, size distribution, resistivity, trace metals, and electrostatic precipitator performance. Concentrations of O_2 and CO_2 were measured in the flue gas for calculating emission rates from the concentrations of the pollutants that were measured. The gaseous concentrations of NO_x, SO_x, CO, HC, halogens, and phosgene were measured.

PLANT DESCRIPTION

The powerhouse of the General Electric Company in Erie, Pennsylvania, is a co-generation facility producing electrical power along with process and heating steam (see Figure 2). The plant has four coal-fired boilers. Three of these boilers are the spreader stoker type with steam-generation capacities of 100,000, 150,000, and 175,000 lb/hr. The fourth boiler has cyclone burners and a steam generation capacity of 340,000 lb/hr. Coal and dRDF blend-firing was tested in the 150,000 lb/hr spreader-stoker unit.

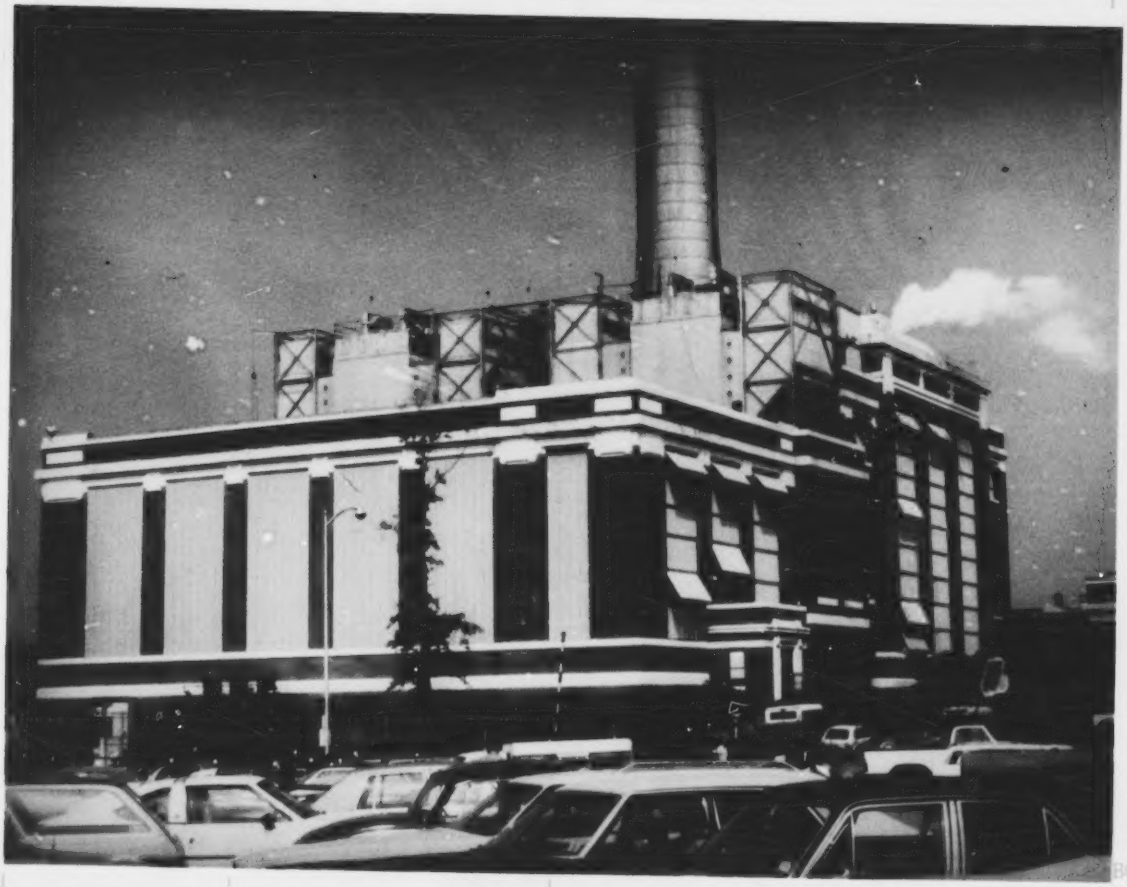

Figure 2. Power plant, General Electric Co., Erie, Pennsylvania.

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Normal operation of the plant consists of the cyclone boiler carrying a base (steady) load while one or more of the spreader-stoker units "take the swings" (respond to variations in steam demand). During the test periods this mode of operation was changed to allow the spreader-stoker to be operated at steady state leaving the cyclone unit to take the swings. The cyclone boiler controls were not designed for nor were the operating personnel accustomed to this mode of operation. As a result, the goal of steady state operation of the test boiler was rarely achieved.

Stoker and Boiler Description

The test boiler was the No. 1 unit of the General Electric Erie Plant Power Station. This unit consisted of a Babcock and Wilcox two-drum Sterling Boiler with a Detroit Rotograte Spreader Stoker. Figure 3 is a cross-sectional view of this 150,000 lb/hr steam generator. Table 5 is the specifications of the B&W boiler. Table 6 includes the specifications of the Detroit Stoker system. Figure 4 is a cross-sectional view of a Detroit spreader and chain grate. This boiler was equipped with Bailey Custom Line pneumatic controls.

Large particulate is collected by a Western Precipitator Multiclone dust collector located between the boiler outlet and the Economizer inlet (see Table 7). In normal operation the fly ash collected by the multiclone dust collector is reinjected with the rear overfire air. To assess the impact this practice has on particulate mass emissions while firing dRDF, the reinjection system was modified. A bypass system was installed that permitted either collection or reinjection of fly ash. As indicated in the April and May schedules, testing was conducted without fly ash reinjection on 4 days. On all four occasions the boiler was operated at full load, with either coal-only or 1:2 Teledyne blend (see Tables 2 and 3).

Final particulate emissions control is accomplished by an electrostatic precipitator. This precipitator was manufactured by UOP and is sized to simultaneously process the flue gases from the test boiler plus another 100,000 lb/hr boiler. A single induced draft fan for both boilers is located at the outlet of the ESP. During test periods the test boiler was operated alone while leaving the 100,000 lb/hr boiler down with its dampers closed. Thus gas velocities through the precipitator during testing were well below design. This precipitator consists of two sections in series, each section having two parallel fields. Table 8 is the specifications of this 2-section, 4-field ESP. Figure 5 shows the location of the sampling ports which were installed to allow emissions testing.

Fuel Handling System

Very little modification of the existing fuel-handling system was required. Only a crusher bypass plate and a backstop at a conveyor transfer were installed. Otherwise the fuel handling system was used as it existed.

Figure 6 is a schematic of the fuel handling system. The pelletized dRDF was brought from the coal yard in dump trucks and poured through the grizzly screen (see Figure 7) and into a hopper with a reciprocating feeder.

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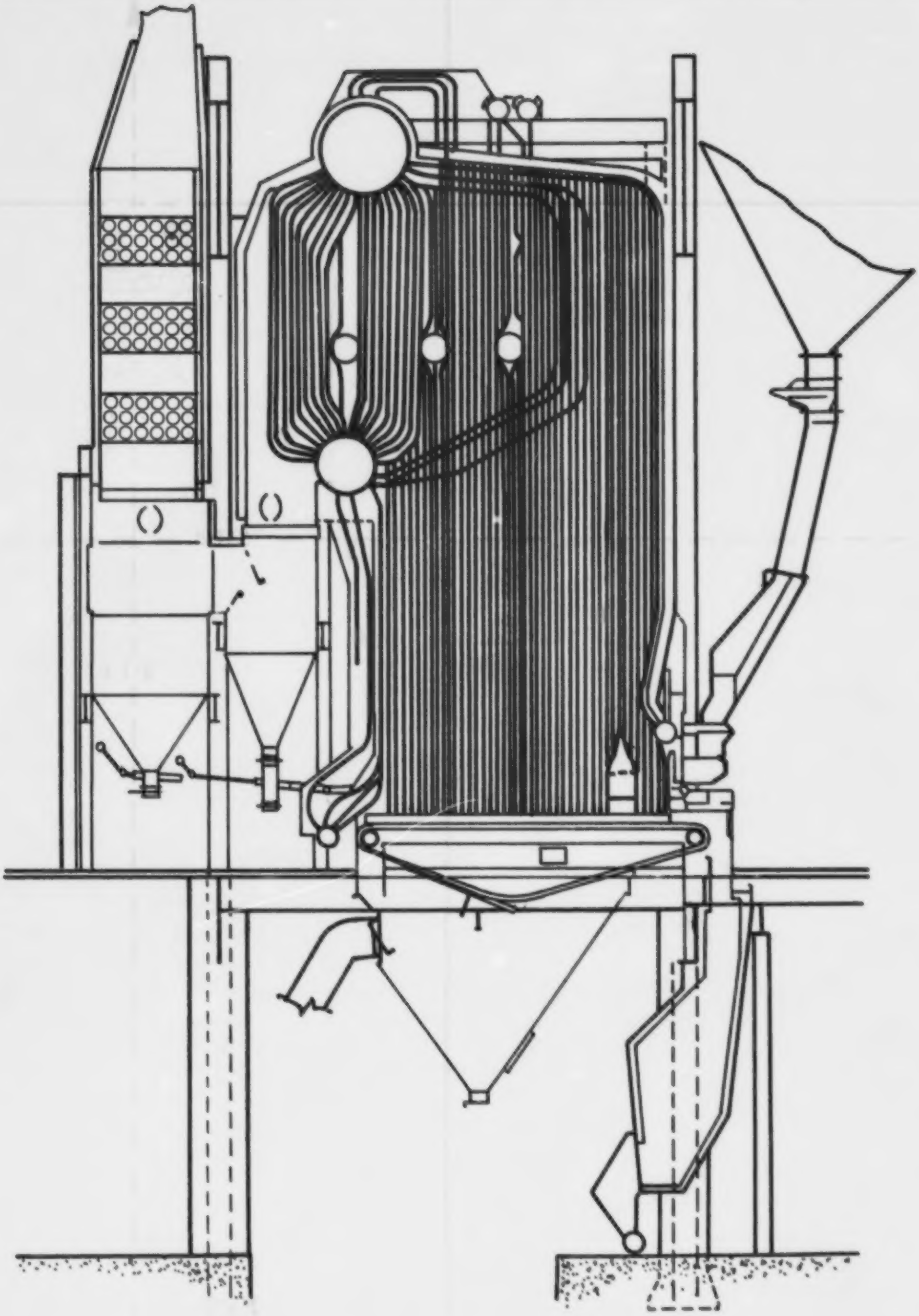

Figure 3. Cross section view of Babcock and Wilcox two-drum Sterling test boiler.

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TABLE 5. DESCRIPTION OF THE NUMBER 1 BOILER, G.E., ERIE, PENNSYLVANIA, BABCOCK AND WILCOX STERLING BOILER

Year built	1949
Babcock and Wilcox contract number	S-9594
National Board H.S.B.	16326
Rated steaming capacity	150,000 lb/hr
Design pressure	675 psig
Steam temperature	825°F
Waster entering economizer temperature	225°F
Flue gas leaving economizer temperature	400°F
Excess air, boiler exit	33 percent
Rated efficiency	84.5 percent
Furnace volume	7,860 ft^3
Furnace liberation	27,900 Btu/hr ft^3
Boiler section heating surface	15,081 ft^2
Waterwall surface	825 ft^2
Superheater surface	4,400 ft^2
Economizer surface	7,878 ft^2
Fuel weight at rated load	17,400 lb/hr
Flue gas weight at rated load	240,000 lb/hr

TABLE 6. DESCRIPTION OF DETROIT ROTOGRATE SPREADER STOKER

Number of spreaders	6
Feeder size	27 in.
Spreader type	reciprocating overthrow
Volumetric capacity	720 ft^3/hr
Forward traveling grate	
Grate width	22 ft, 7 1/2 in.
Grate length	16 ft, 8 in.
Grate area	376 ft^3

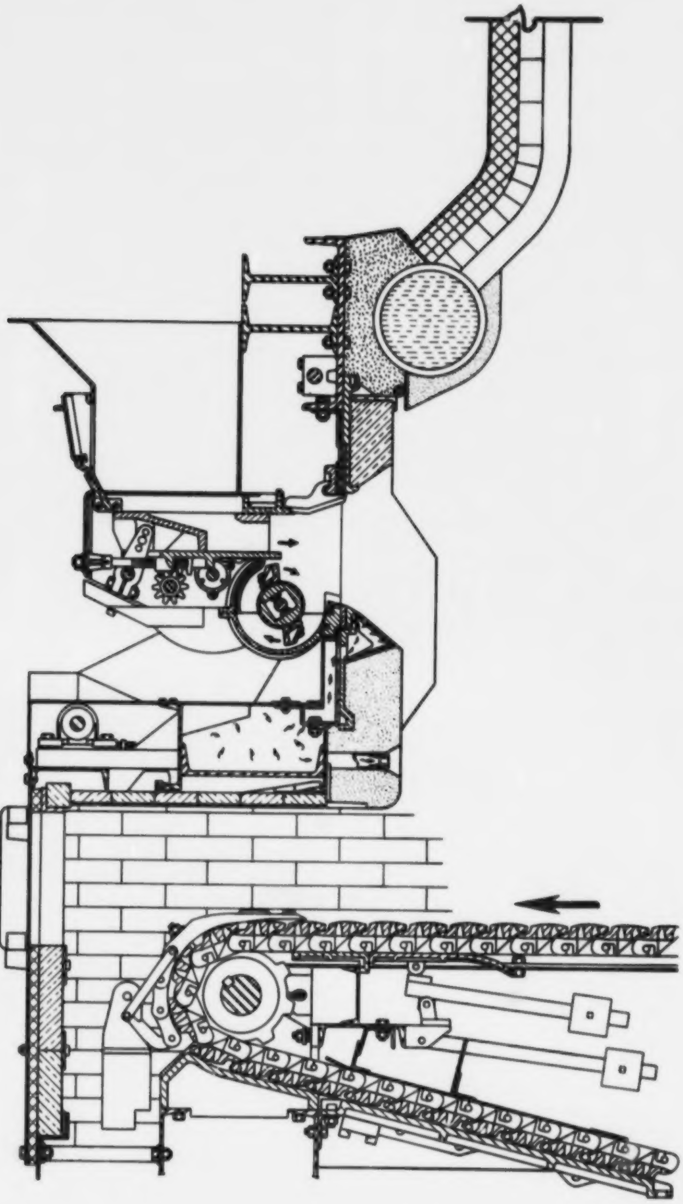

Figure 4. Cross-sectional view of Detroit Stoker Rotograte spreader and grate.

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TABLE 7. DESCRIPTION OF W-P MULTICLONE DUST COLLECTORS

Western Precipitator	
Multiclone collector	
Type	9VG12
Size	196-7
Model	P-17296-A
Serial number	1724
Draft consumption	4 in. H_2O
Gas volume	169,500 ACFM
Gas temperature	780°F
K factor	12.3
Number of cyclones	196
Cyclone diameter	9 in.
Cyclone entrance	Side
Cyclone exit	Top

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TABLE 8. SPECIFICATION OF UOP ELECTROSTATIC PRECIPITATOR

Year installed	1973
Model number	24(99)29-1-2
Flow	133,000 ACFM @ 480°F
Gas passages per field	29
Number of collector plates	116
Collected plate size	9 ft × 24 ft
Total effective collection area	25,056 ft^2
Specific collector area (SCA)	188 ft^2
Mechanical fields	2 each, 9 ft long
Power supply, each field	800 ma TR's
Efficiency	94 percent

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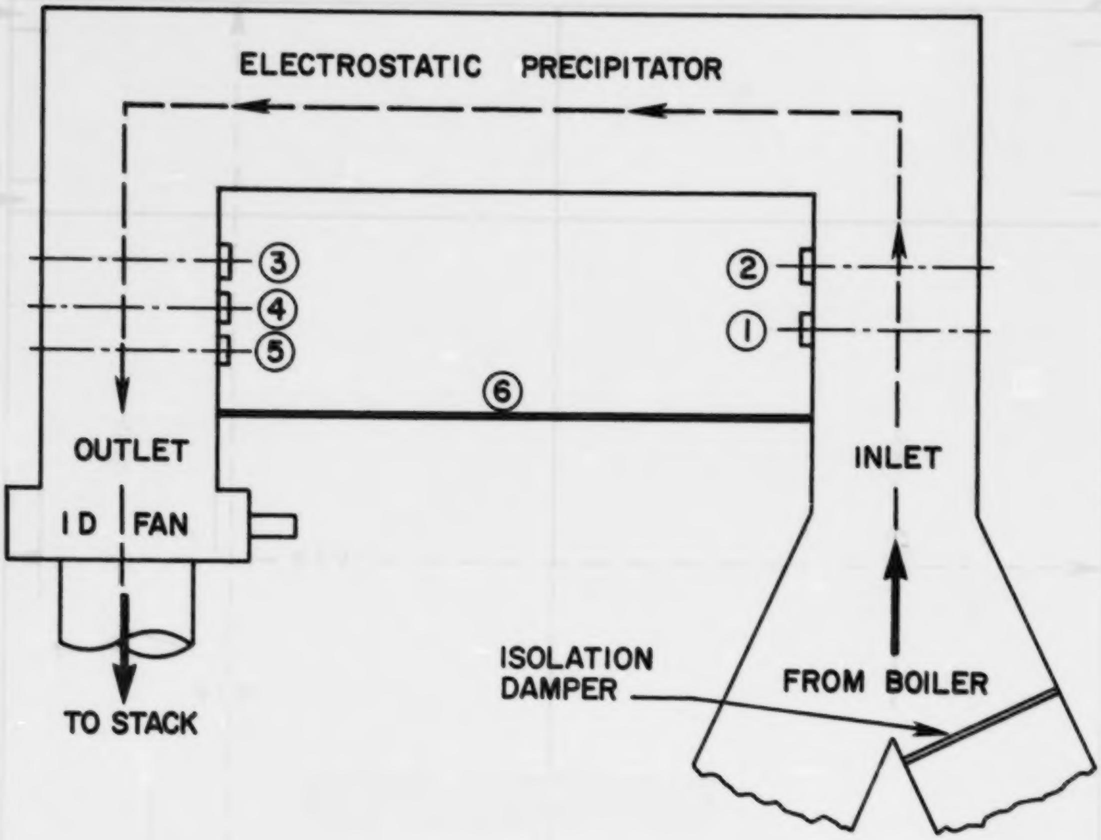
ELECTROSTATIC PRECIPITATOR
③
④
⑤
②
①
⑥
OUTLET
INLET
ID FAN
ISOLATION DAMPER
FROM BOILER
TO STACK

① SINGLE SAMPLING PORT FOR FLUE GAS CHARACTERIZATION

② 5 @ METHOD FIVE SAMPLING PORTS ON VERTICAL DUCT WALL OF INLET (existing)

③ 5 @ METHOD FIVE SAMPLING PORTS ON VERTICAL DUCT WALL OF OUTLET (existing)

④ GAS SAMPLING PORT FOR CONTINUOUS FLUE GAS MONITOR

⑤ GRAB SAMPLING PORT FOR FLUE GAS CHARACTERIZATION

⑥ CATWALK SAMPLING PLATFORM

Figure 5. Plan view of ESP and modifications for sampling.

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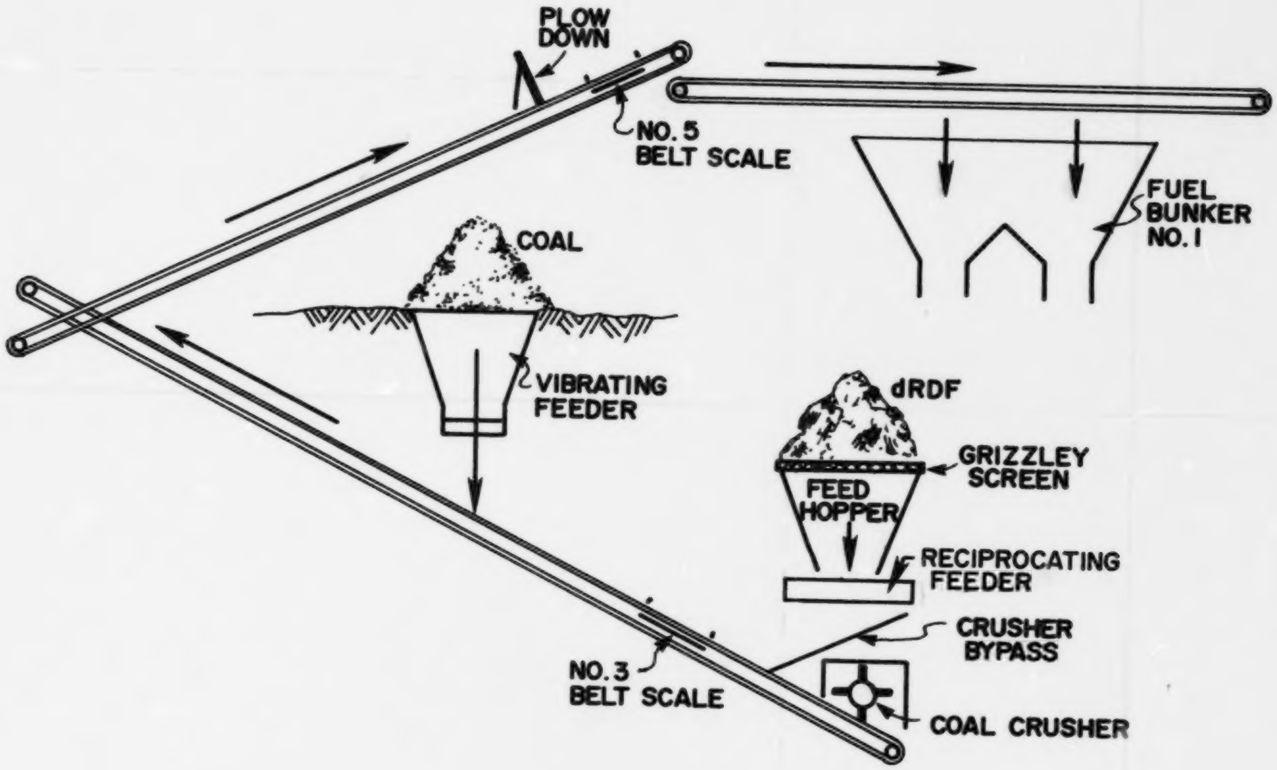
PLOW DOWN
NO. 5 BELT SCALE
FUEL BUNKER NO. 1
COAL
VIBRATING FEEDER
dRDF
GRIZZLEY SCREEN
FEED HOPPER
RECIPROCATING FEEDER
CRUSHER BYPASS
NO. 3 BELT SCALE
COAL CRUSHER

Figure 6. Material handling system for blending fuel.

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Figure 7. Offloading dRDF through the grizzly screen.

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A crusher bypass plate diverted the flow away from the crusher inlet and directly onto the conveyor. As the dRDF was transported on the belt conveyor, the vibratory feeder fed the previously crushed coal (from the outdoor storage pile) onto the top of the dRDF. After a few transitions from one conveyor to another the blend was thoroughly mixed.

The ratio of the blend was controlled by use of three devices; two belt scales, and a variable speed vibratory feeder. The first belt scale (Number 3) was located upstream of the vibratory feeder. This scale displayed the weight of the dRDF. The second belt scale (Number 5) displayed the weight of the coal and dRDF blend. By varying the speed of the vibratory feeder the ratio of coal to dRDF could be controlled.

Since scoops of uncrushed coal were used to anchor the dRDF covers in the coal yard, lumps of uncrushed coal were carried in with the dRDF. Therefore it was necessary to inspect the fuel on the conveyor and hand pick the large coal chunks that could clog the stoker.

The coal/dRDF blend was transported from the second belt scale (Number 5) to the bunker by a series of belt conveyors. A "till" was used to dump the fuel blend off the belt and into the bunker. To assure level and uniform filling of the divided bunker, a technician moved the till from one side of the bunker to the other side of the bunker every 5 minutes.

Pretest Power Plant Preparation

Boiler No. 1 was overhauled in the summer of 1978. At that time the spreader stokers, grate, and drive train were reconditioned. A new air distribution box and new injection tubes were installed on the front wall. Also new plastic refractory was installed on the front wall, and all boiler tubes were deslagged.

In December 1978 Mr. Argo Kraus, a retired Detroit Stoker Field Engineer, inspected the grate and spreaders. At that time the unit had logged 3,000 hours of operation since its overhaul in the previous summer. The following repairs were made as a result of Mr. Kraus' recommendations.

1. Spill plates were uniformly adjusted.
2. Coal feed multiple linkage was indexed.
3. Woodruff key replaced on feed plate drive shaft of No. 3 feeder.
4. Rear wall refractory was repaired.
5. Rear grate turners were cleaned and repaired.
6. A number of rotor blades were replaced.
7. Appropriate rotor blades were installed on the end feeders to prevent fuel impingement on the side walls.
8. Refractory on the front casing was repaired.
9. Superheater, economizer, and front wall tubes were deslagged.

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Mr. Kraus also made the following observations about the condition of the stoker system:

1. Rails between the grates were worn to the point of causing damage to the grate itself.
2. Frames of the ash doors were broken and permitted excess air leaks.
3. The ash pit had no refractory to seal air leaks.
4. Several lower grate seal plates were warped.
5. One grate end seal casting was missing.

All of these conditions, unless corrected, would cause less than ideal underfire air distribution.

To minimize tramp air, the boiler casing was checked for leaks. This check was performed by closing all access doors and the ID fan damper. A smoke bomb was placed on the grate, and the forced draft fan was turned on. These conditions caused the boiler and furnace interiors to experience a positive static pressure. Smoke was expelled out of all the cracks in the boiler casing. The locations of these leaks were marked and later sealed. As a result of this leak sealing, the boiler was able to operate at 30 to 40 percent excess air. However, the operators were not accustomed to maintaining this minimum excess air level, and the actual levels experienced during the test were frequently higher.

Sampling ports and view ports were installed on the boiler for combustion gas characterization and flame pattern observations. Locations of view ports and sampling ports are indicated in Figure 8. Also shown in this Figure are all modifications made to the system in preparation for testing.

Bailey Meter Division of Babcock and Wilcox subcontracted to supply a technician to inspect, repair, and calibrate the controls and instruments installed with this 30 year old steam generator. The entire control system was serviced including totalizing relays; pilot valve assemblies; and control drives for fuel, forced draft, and induced draft. When operated in the automatic mode, the system's response to load changes was only marginally acceptable because of the age and condition of this equipment.

FUELS DESCRIPTION

Two types of densified refuse derived fuel were co-fired with coal. During March 492 tons of 1/2 in. × 1 in. pellets produced at the National Center for Resource Recovery (NCRR) were test fired. In April and May 1256 tons of 1/2 in. × 1 in. pellets produced by Teledyne National Corporation were test fired. For the first test week in March and the last test week in May coal alone was fired. Coal-only firing was performed to provide a baseline for comparison of the dRDF test results.

It was desirable to fire dRDF at as high a substitution rate as possible. But less than 500 tons of NCRR pellets were available. Therefore all testing with NCRR pellets was conducted at a volumetric blend ratio of

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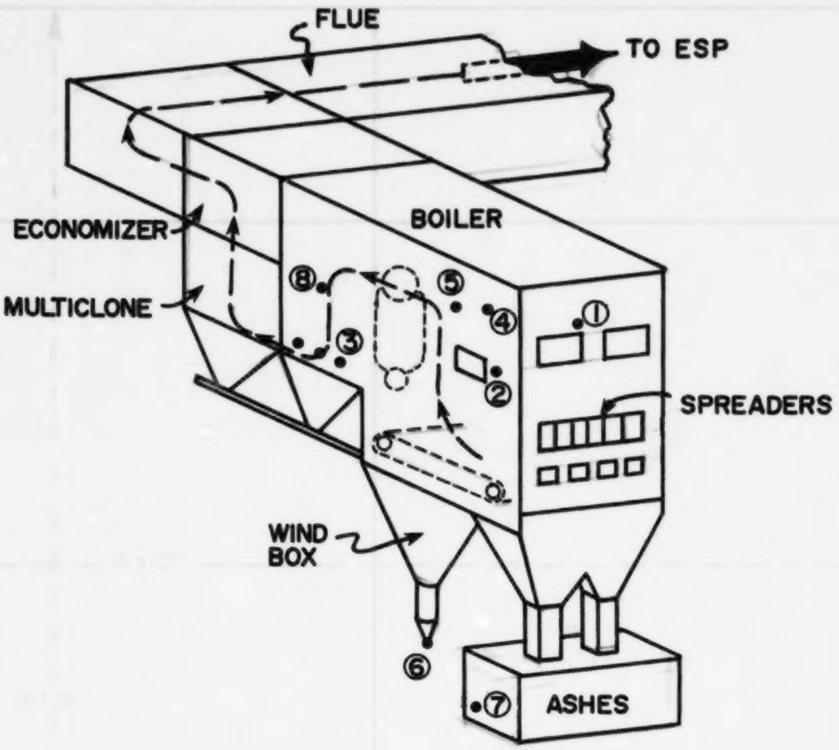
FLUE
TO ESP
ECONOMIZER
MULTICLONE
BOILER
①
②
③
④
⑤
⑥
⑦
⑧
SPREADERS
WIND BOX
ASHES

① VIEW PORTS IN FRONT OF BOILER FOR LOOKING INTO SCREENTUBES AND SUPERHEATER

② VIEW PORT AT PEAK OF FUEL TRAJECTORY FROM SPREADER

③ BOILER OUTLET PARTICULATE SAMPLING PORTS

④ SCREENTUBE GAS TEMPERATURE

⑤ CONVECTIVE SECTION GAS TEMPERATURE

⑥ DRAIN IN WINDBOX TO COLLECT GRATE SIFTINGS

⑦ CHUTES TO MANUALLY REMOVE ASHES INTO TRUCK FOR WEIGHING

⑧ SAMPLING PORT FOR FLUE GAS

Figure 8. Modification to boiler for testing.

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one part coal to two parts dRDF. Table 9 indicates the various equivalent methods of expressing the blend ratios of coal and NCRR pellets.

TABLE 9. EQUIVALENT FUEL BLENDS FOR NCRR dRDF

Coal*	11,805 Btu/lb	52 lb/ft^3
dRDF	5,269 Btu/lb	34 lb/ft^3

Nominal blend coal:dRDF by volume	Blend weight ratio coal:dRDF	dRDF heat substitution percent dRDF
1:0	1:0	0
1:1	1:0.65	23
1:2	1:1.31	37
1:4	1:2.61	54

* Average of as-received values for all coals used during test sequence.

The Teledyne pellets were tested at blend volumetric blend ratios of 1:1, 1:2, and 1:4. The equivalent methods of expressing Teledyne dRDF blend ratios are shown in Table 10.

TABLE 10. EQUIVALENT FUEL BLENDS FOR TELEDYNE dRDF

Coal*	11,805 Btu/lb	52 lb/ft^3
dRDF	6,092 Btu/lb	33 lb/ft^3

Nominal blend coal:dRDF by volume	Blend weight ratio coal:dRDF	dRDF heat substitution percent dRDF
1:0	1:0	0
1:1	1:0.63	25
1:2	1:1.27	40
1:4	1:2.53	57

* Average of as-received values for all coals used during test sequence.

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Fuel Storage

The dRDF was stored in windrows in the coal yard of the General Electric Company plant (see Figure 9). NCRR pellets were delivered in October and November 1978. These same pellets were used in March 1979, thus they were stored in the coal yard for a period of 4 to 5 months in winter weather. Prior to coal yard storage these pellets were stored for up to 1 1/2 years in Washington, D.C. The Teledyne pellets were delivered from November 1978 through April 1979. These pellets were fired in April and May 1979 and so had experienced a storage period of 1 to 6 months of Lake Erie's winter and spring weather.

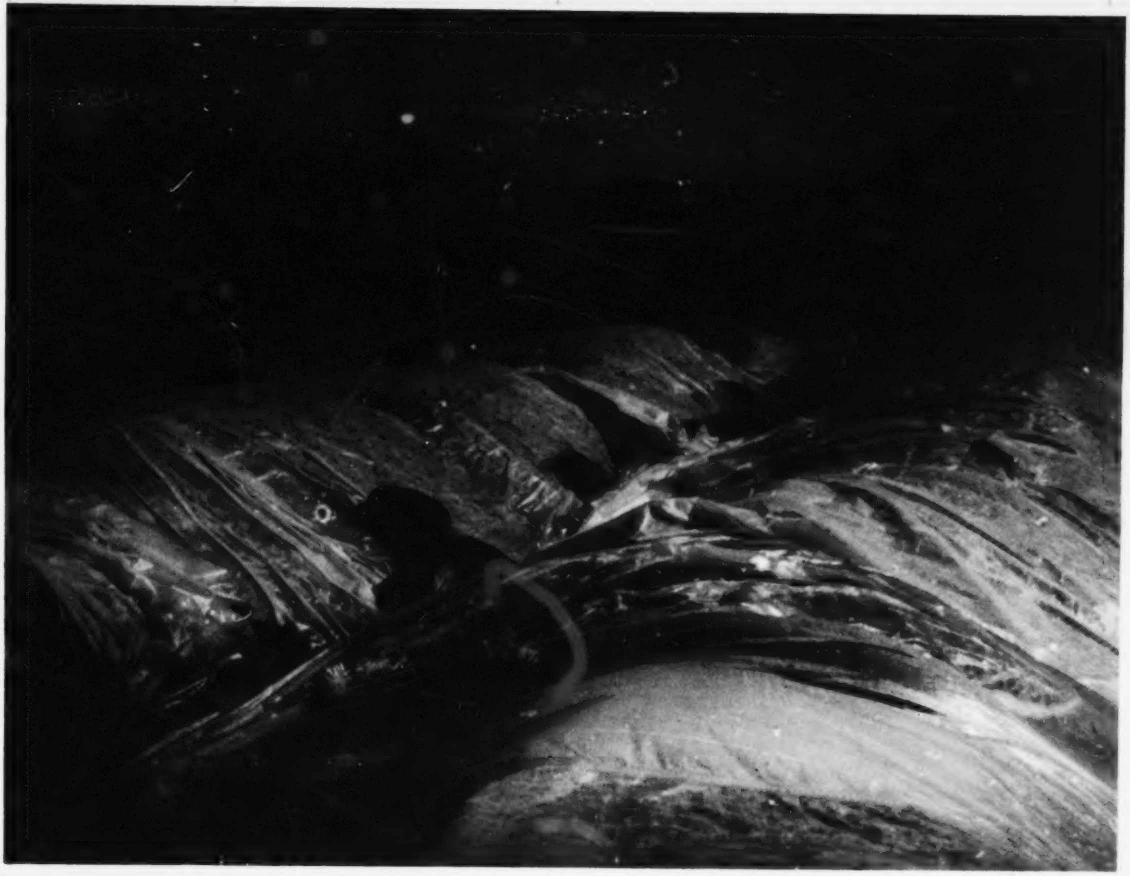

Figure 9. Windrows of dRDF in coal yard.

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All pellets were delivered by truck and unloaded into windrows. A front end loader shaped these windrows to 7 ft high. A 4- to 6-in. bed of coal formed the surface upon which the pellets were stored. This coal bed was intended to keep the pellets isolated from surface water. This coal yard was located near the southeast shore of Lake Erie, and the winter weather at this location is very severe. The pellets were initially covered with 6 mil polyethylene coverings held in place with old tires. The high winds quickly removed these covers, leaving the pellets exposed to the weather. With the polyethylene covers again stretched in place, scoops of coal were poured over each cover to anchor it. The cold weather embrittled the polyethylene and the high winds fatigued and ripped the covering away. Six mil, nylon reinforced covering was then purchased and used. Again the winter weather embrittled and ripped away the polyethylene, leaving only a mesh of the nylon reinforcement covering the pellets (see Figure 10).

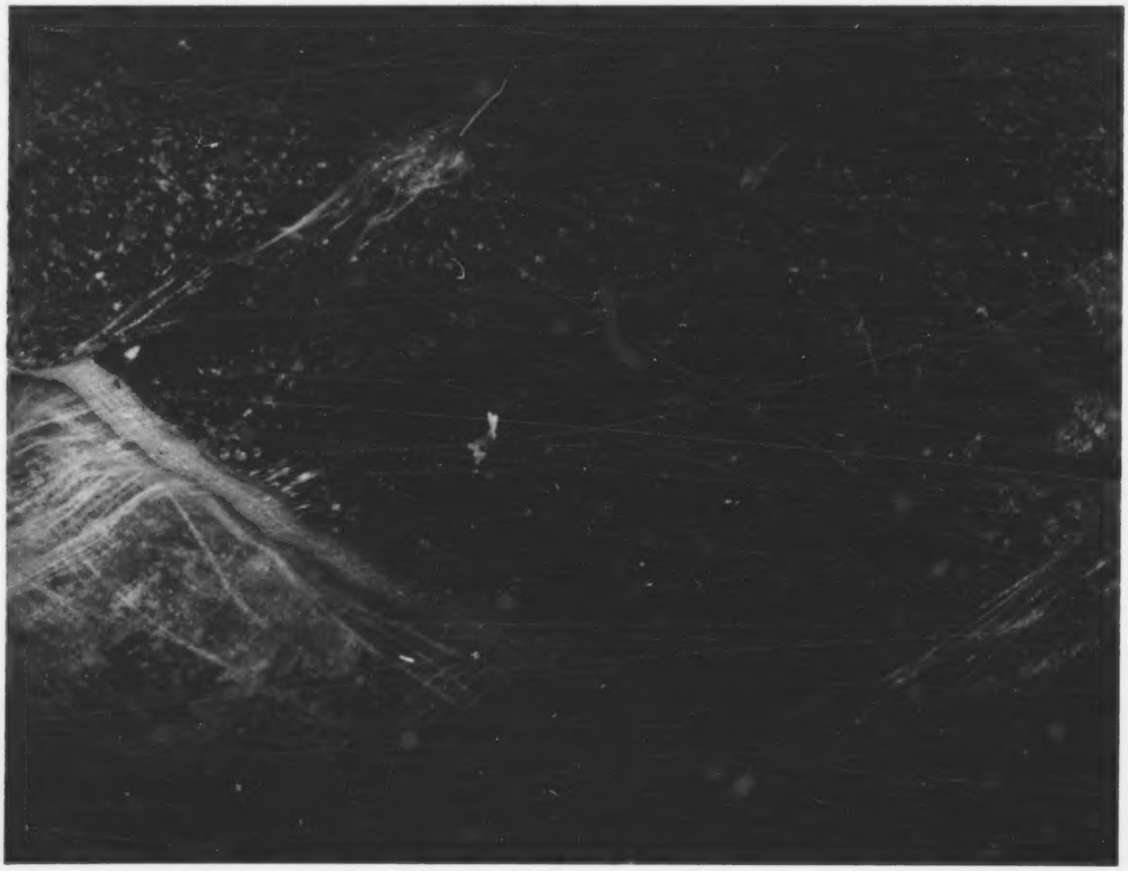

Figure 10. Ripped dRDF pellet cover.

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Fuel Properties

Attempts were made to fire a constant coal type during all coal baseline and blend tests. However, coal delivery schedules of the several suppliers used made such attempts unsuccessful. Fortunately the coal properties were reasonably consistent during any individual week. Coal and dRDF types used during each test week are shown in Table 11.

TABLE 11. BURN SCHEDULE BY FUEL TYPE

Dates	Coal type*	dRDF type*
March 5 - March 9	A	---
March 12 - March 16	B	N**
April 18 - April 25	C	T***
May 7 - May 11	D	T
May 14 - May 18	E	---

* Properties of each coal and dRDF type are described in Table 12.
** NCRR
*** Teledyne

Table 12 lists the properties of the coal and the dRDF on a dry weight basis. Samples of the coal and dRDF were composited on a daily basis. These samples were then subjected to Proximate Analysis, Ultimate Analysis, and Heating Value Analysis. Averages of these analyses form Table 12.

TABLE 12. FUEL ANALYSIS (PERCENT DRY WEIGHT BASIS)

Fuel type	dRDF N	dRDF T	Coal A	Coal B	Coal C	Coal D	Coal E
Fixed carbon	14.7	13.1	48.5	46.6	52.3	54.6	54.7
Volatile matter	54.5	72.6	36.1	35.1	34.8	35.9	35.2
Ash	30.7	13.8	15.6	18.2	12.9	9.5	10.1
Hydrogen	4.6	6.1	4.8	4.6	5.0	4.8	4.9
Carbon	40.6	45.7	68.5	65.2	71.3	73.1	74.8
Nitrogen	0.59	0.37	1.06	1.02	1.21	1.27	1.25
Sulfur	0.43	0.23	4.15	6.78	2.20	1.73	2.09
Chlorine	0.31	0.38	0.14	0.14	0.16	0.12	0.16
Oxygen	22.7	32.9	5.8	4.1	7.2	9.5	6.7
HHV (Btu/lb)	6,755	8,123	12,324	11,872	12,500	12,817	13,281
Density (lb/ft3)	33.6	32.6	51.5	53.8	51.0	53.1	53.1

Figure 11 shows the ash fusion temperature behavior of the various fuels. The initial deformation, softening, hemispherical, and fluid temperatures are shown for each of the five coal types and both dRDF types. All blend results are for the 1:2 (coal:dRDF) volumetric ratio.

The mineral analysis of the coal and dRDF are presented in Appendix D, entitled "Evaluation of dRDF/Coal Fuel and Ash Deposits."

Both types of dRDF were shaped as cylindrical pellets 1/2 in. in diameter with lengths varying from 1/2 in. up to 2 in. In handling, shipment, and storage a portion of the pellets deteriorated to "fines." Fines is defined as the portion of the dRDF that passes a 3/8-in. sieve. This portion of the dRDF was determined on a daily basis and is reported in Table 13. Coal size distributions and blended fuel size distributions are reported graphically in Figures 12 through 19. These plots also show the range of acceptable coal sizes for spreader stoker fired boilers as recommended by the ABMA. Figure 12 represents the size distribution of the coal used in the first coal baseline test which occurred in March. As this Figure indicates, the coal was higher in fines content and had a generally smaller size distribution than is recommended for the test boiler.

When the coal depicted in Figure 13 was blended with NCRR pellets having a 47 percent fines content, the resultant fuel blend had the size distribution plotted in Figure 14. As Figure 13 indicates, this coal alone was within the recommended stoker coal size distribution. But when this coal (with 60 percent fines) was mixed with pellets having 47 percent fines, the resulting blend had 70 percent (<3/8 in.) fines and a size distribution slightly smaller than recommended.

April and May coal that was blended with Teledyne pellets had size distributions shown in Figures 15 and 16, respectively. When blended with pellets having a fines content of about 28 percent, these coal and pellet blends had size distributions shown in Figures 16 and 18. As these figures indicate, the amount of fines was higher than recommended. This size range was not appreciably affected after the pellets were blended into the coal.

As Figure 19 shows, the May coal baseline fuel had 80 percent fines, which is well in excess of the typical 50 percent recommended for use in a spreader stoker.

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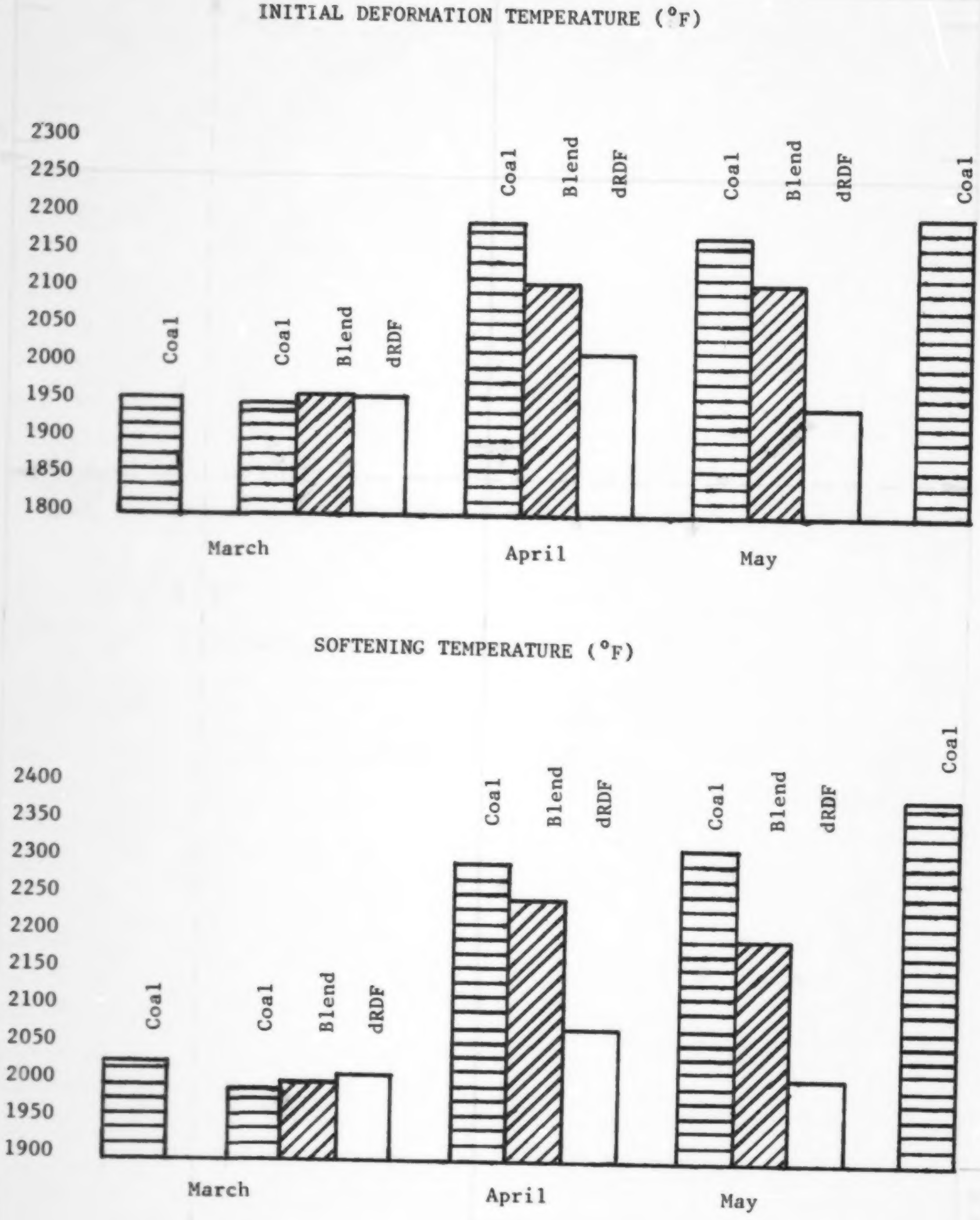

Figure 11. Fusion temperature analysis of fuels.

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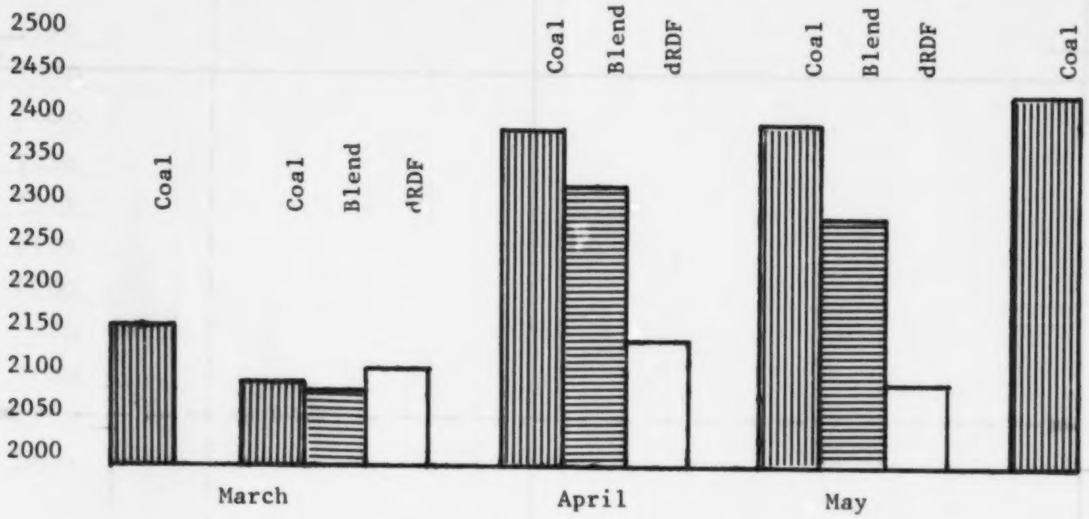

FLUID TEMP REDUCING CONDITIONS (°F)

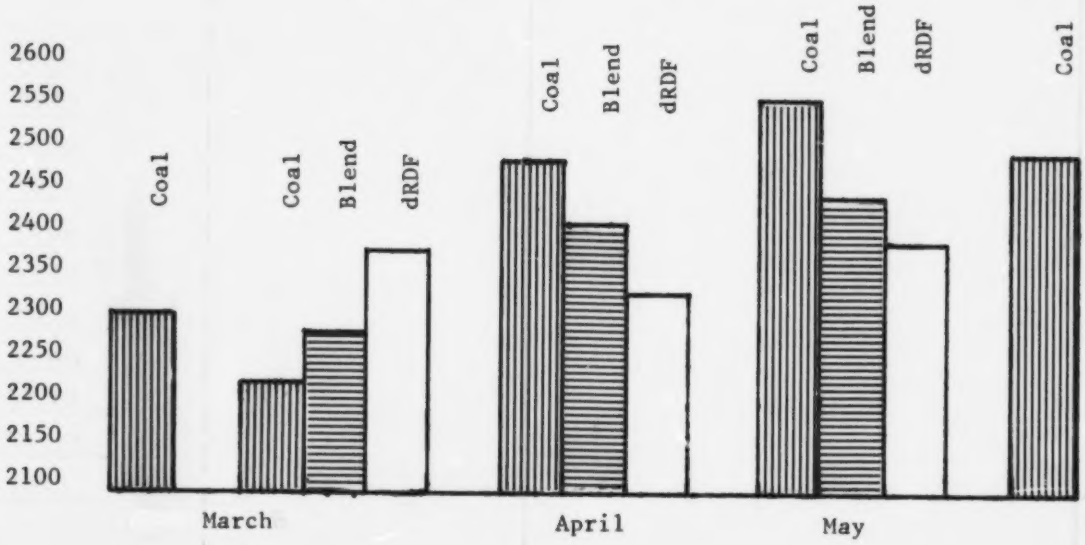

Figure 11. (continued)

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TABLE 13. dRDF FINES (PERCENT BY WEIGHT PASSING 3/8 IN. SIEVE)

Date	Fuel type	Percent	
March 13	N	54.3	
March 14	N	52.2	46.7 avg
March 15	N	39.1	
March 16	N	41.0	
April 18	T	10.1	
April 19	T	20.2	
April 20	T	33.3	
April 21	T	21.7	27.8 avg
April 23	T	19.5	
April 24	T	41.7	
April 25	T	47.9	
May 7	T	26.7	
May 8	T	23.7	
May 9	T	34.3	28.0 avg
May 10	T	25.1	
May 11	T	30.3	

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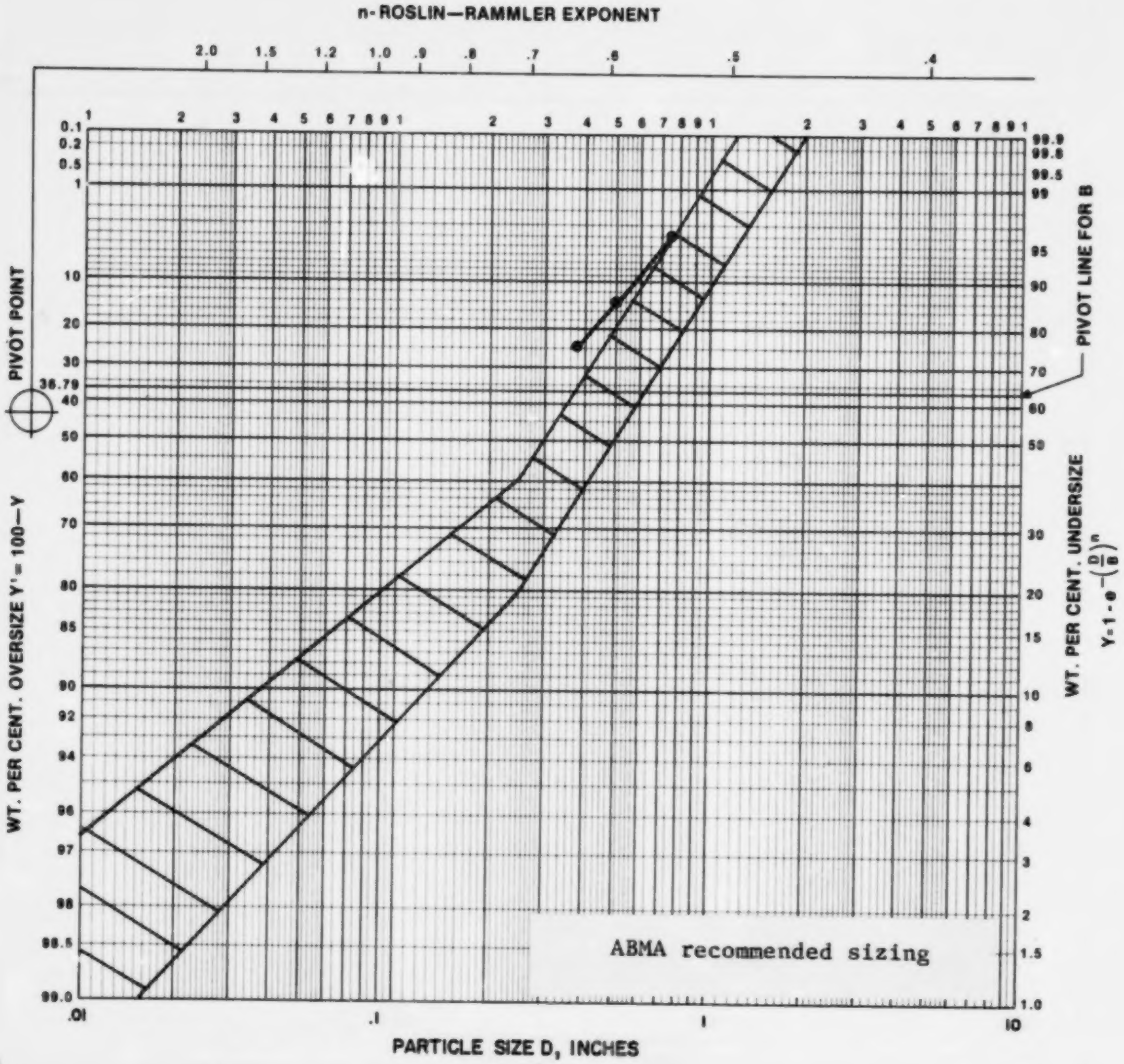

Figure 12. March baseline coal size distribution.

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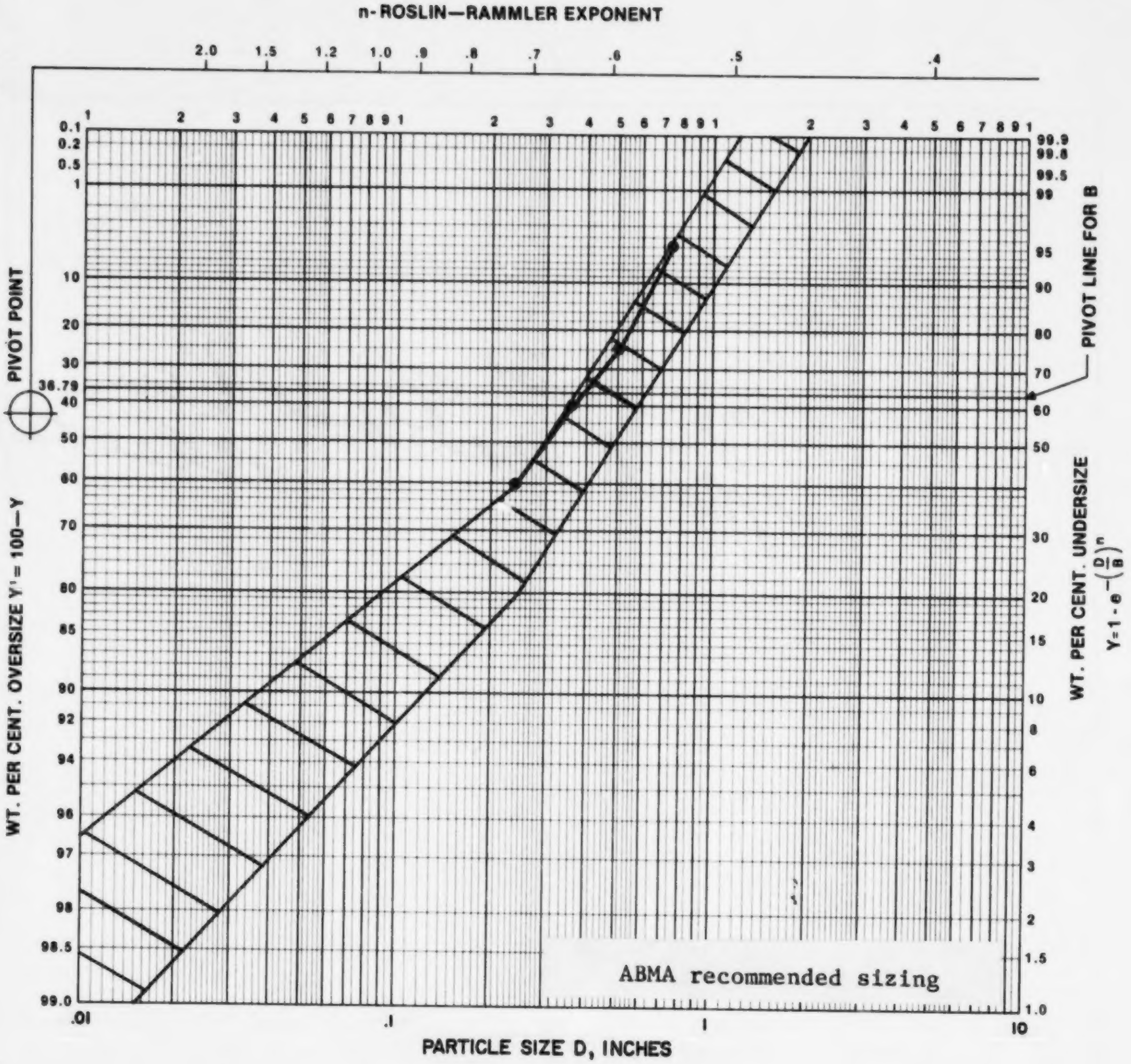

Figure 13. Size distribution of March coal used in blend.

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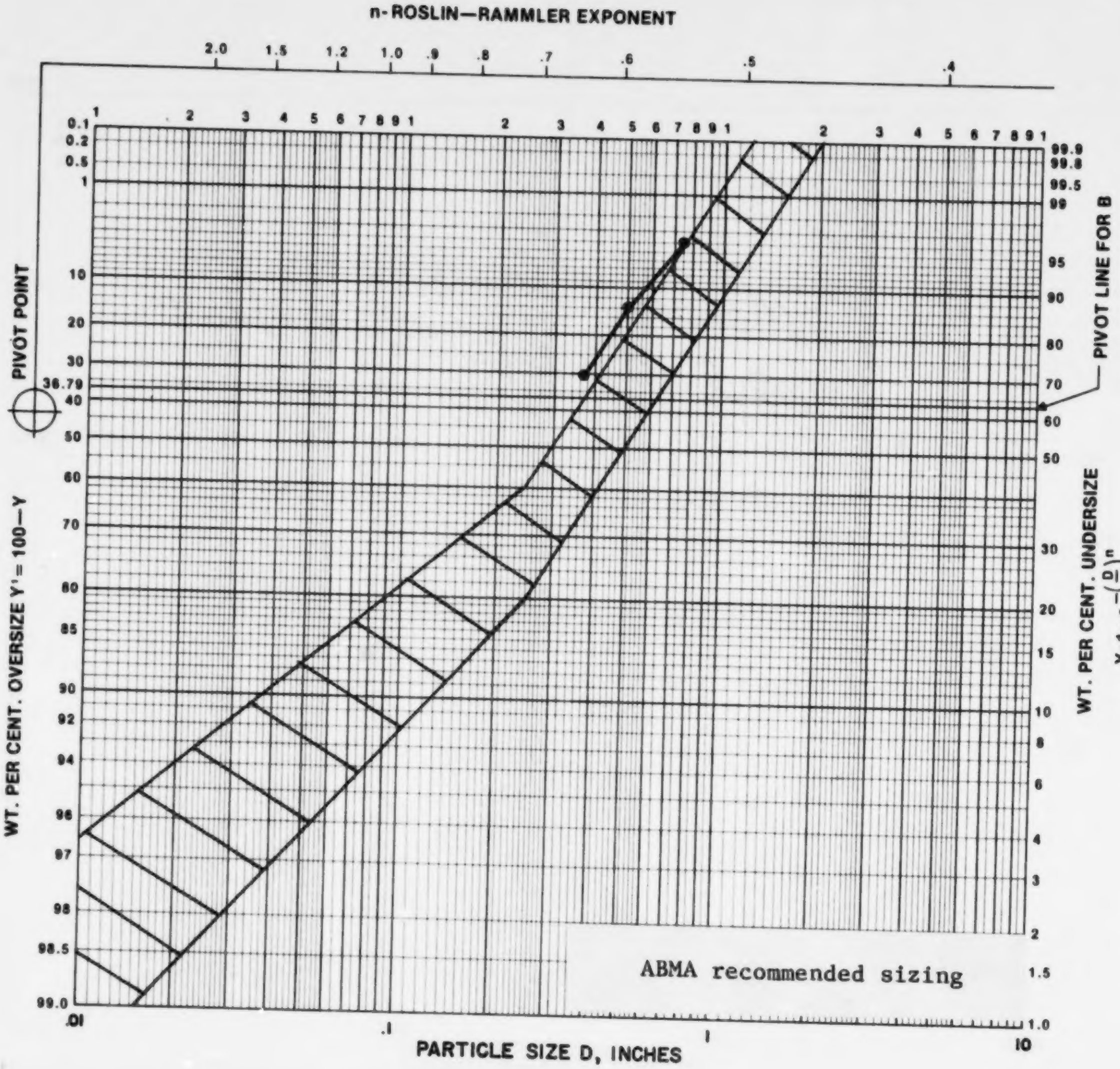

Figure 14. March blend coal/dRDF size distribution.

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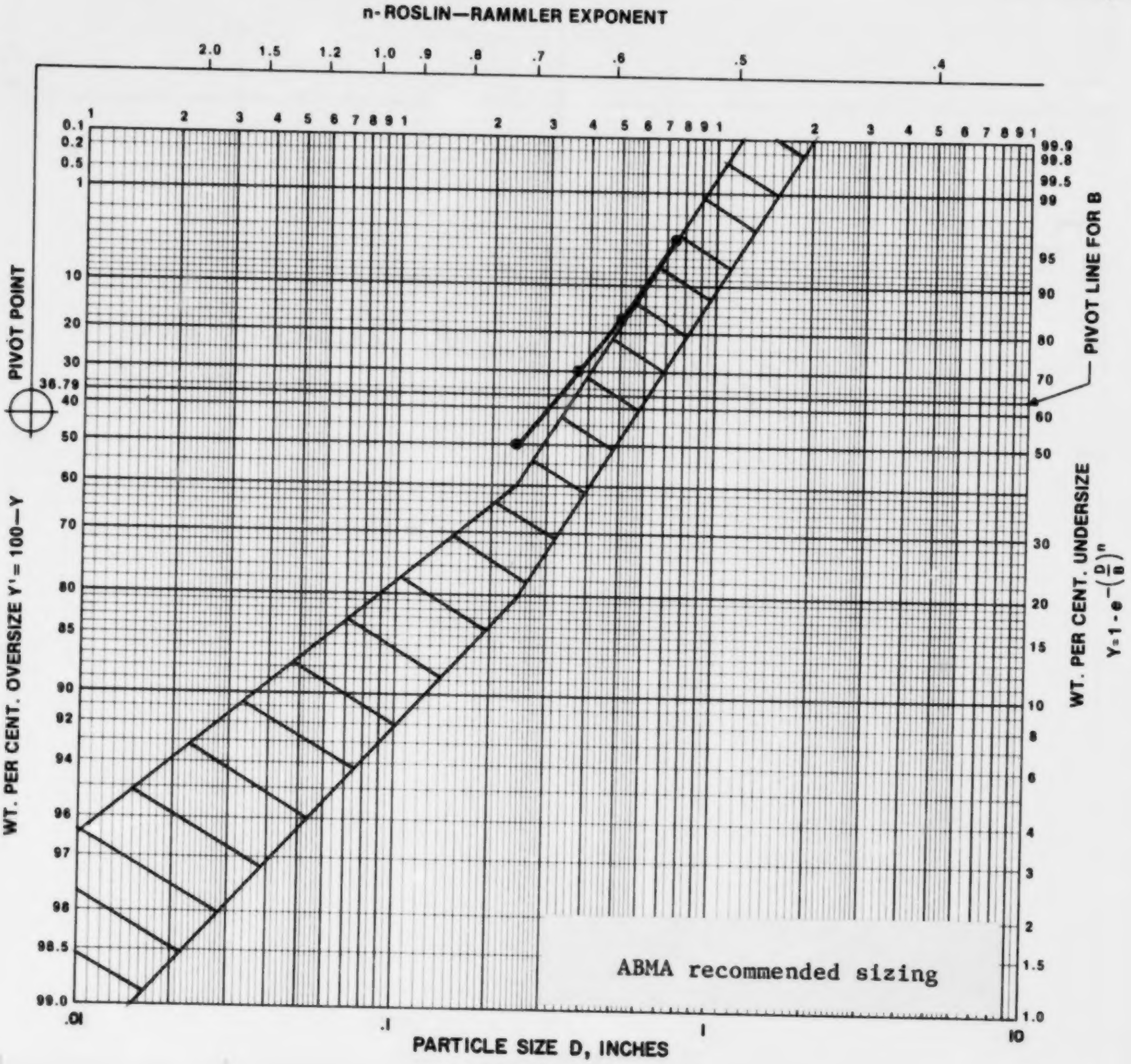

Figure 15. Size distribution of April coal used in blend.

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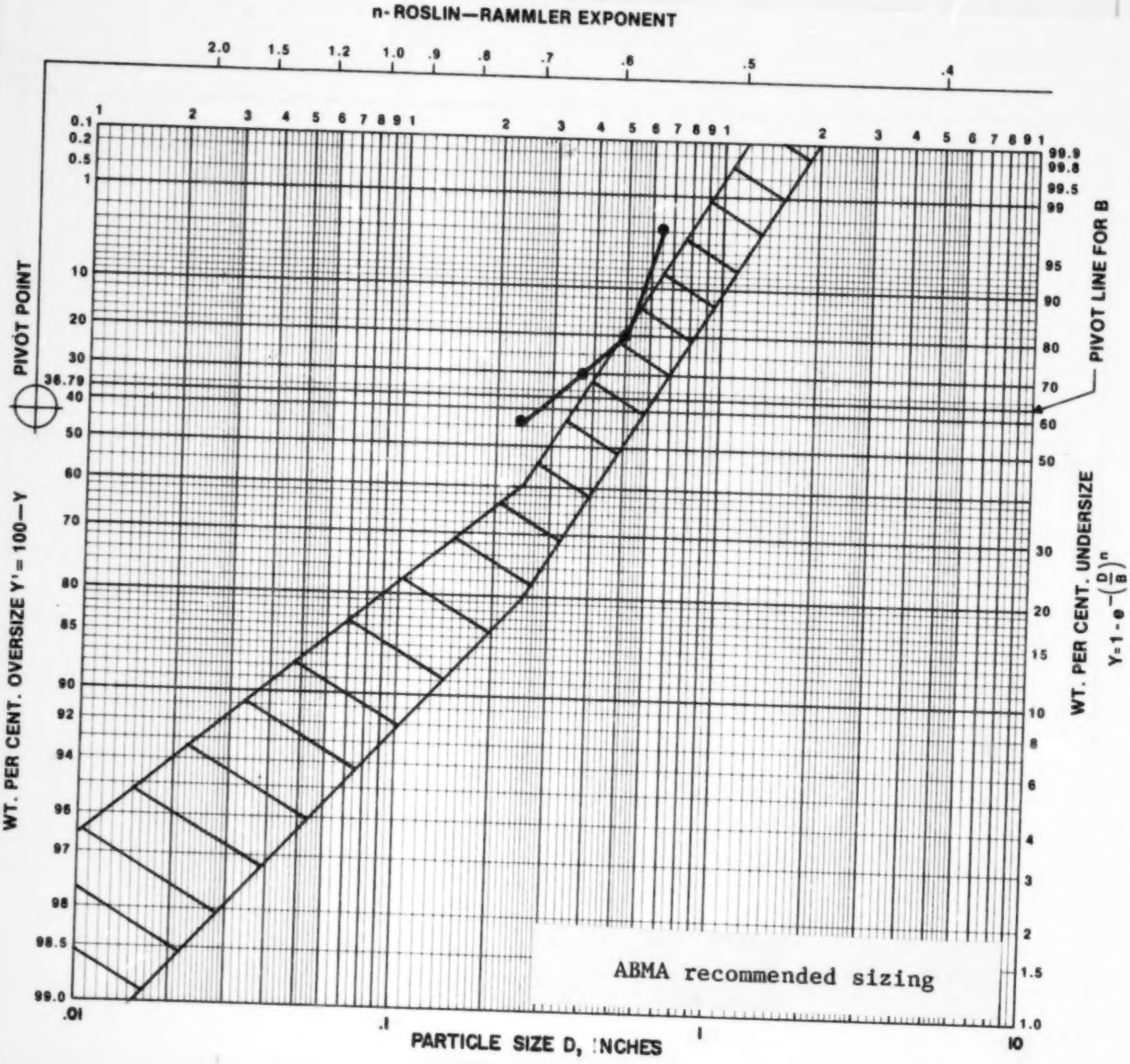

Figure 16. April blend coal/dRDF size distribution.

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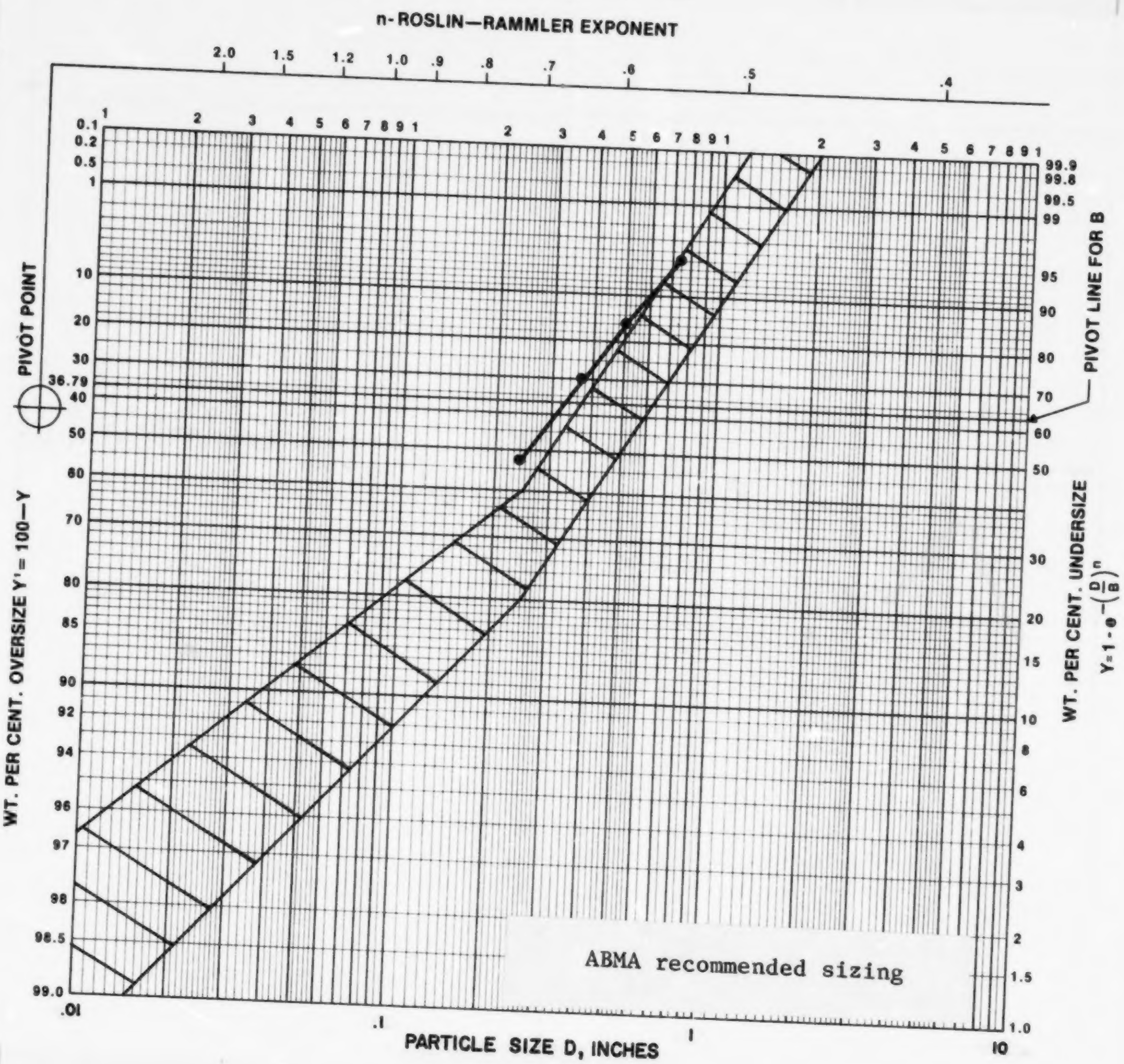

Figure 17. Size distribution of May coal used in blend.

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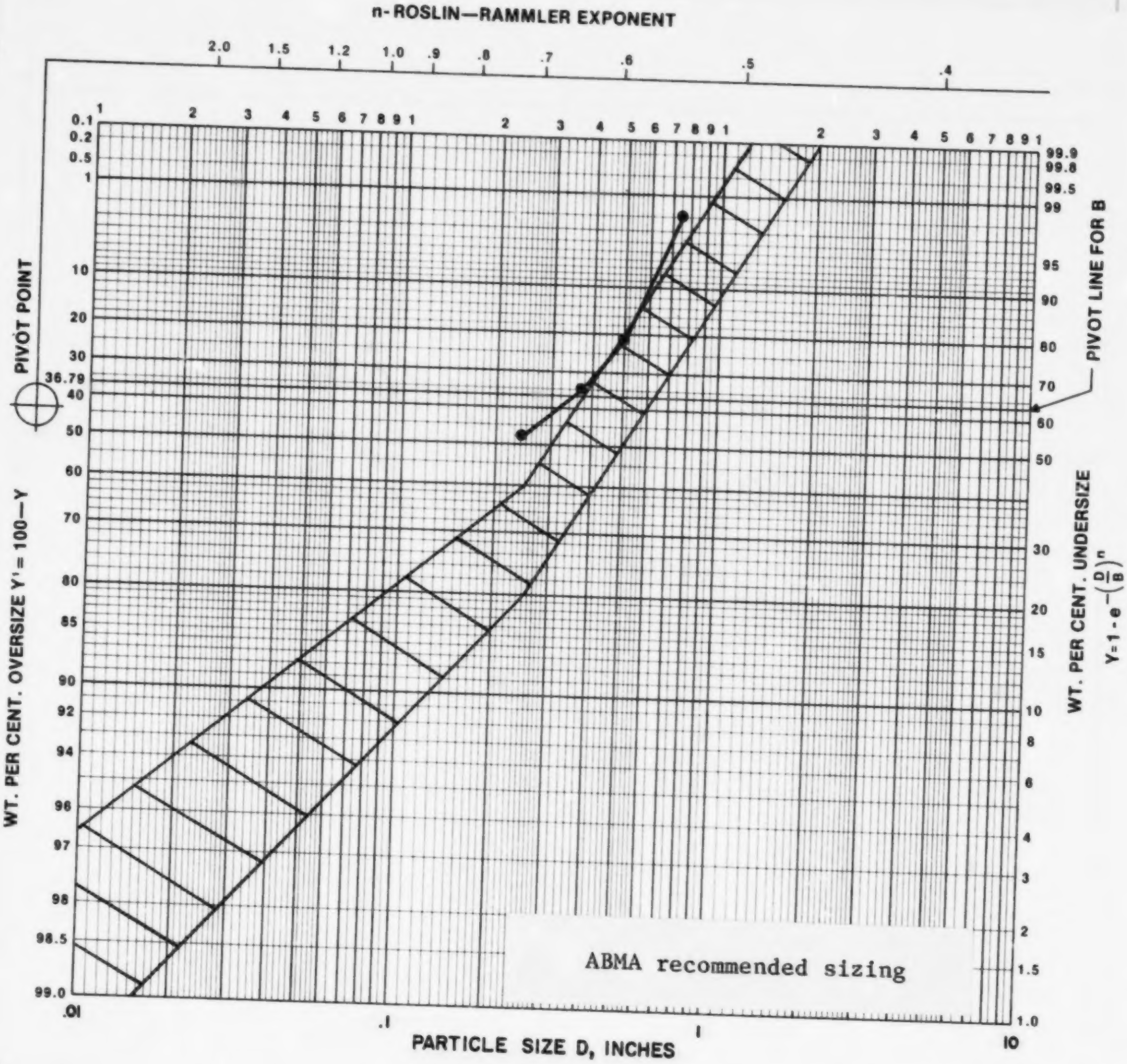

Figure 18. May coal/dRDF blend size distribution.

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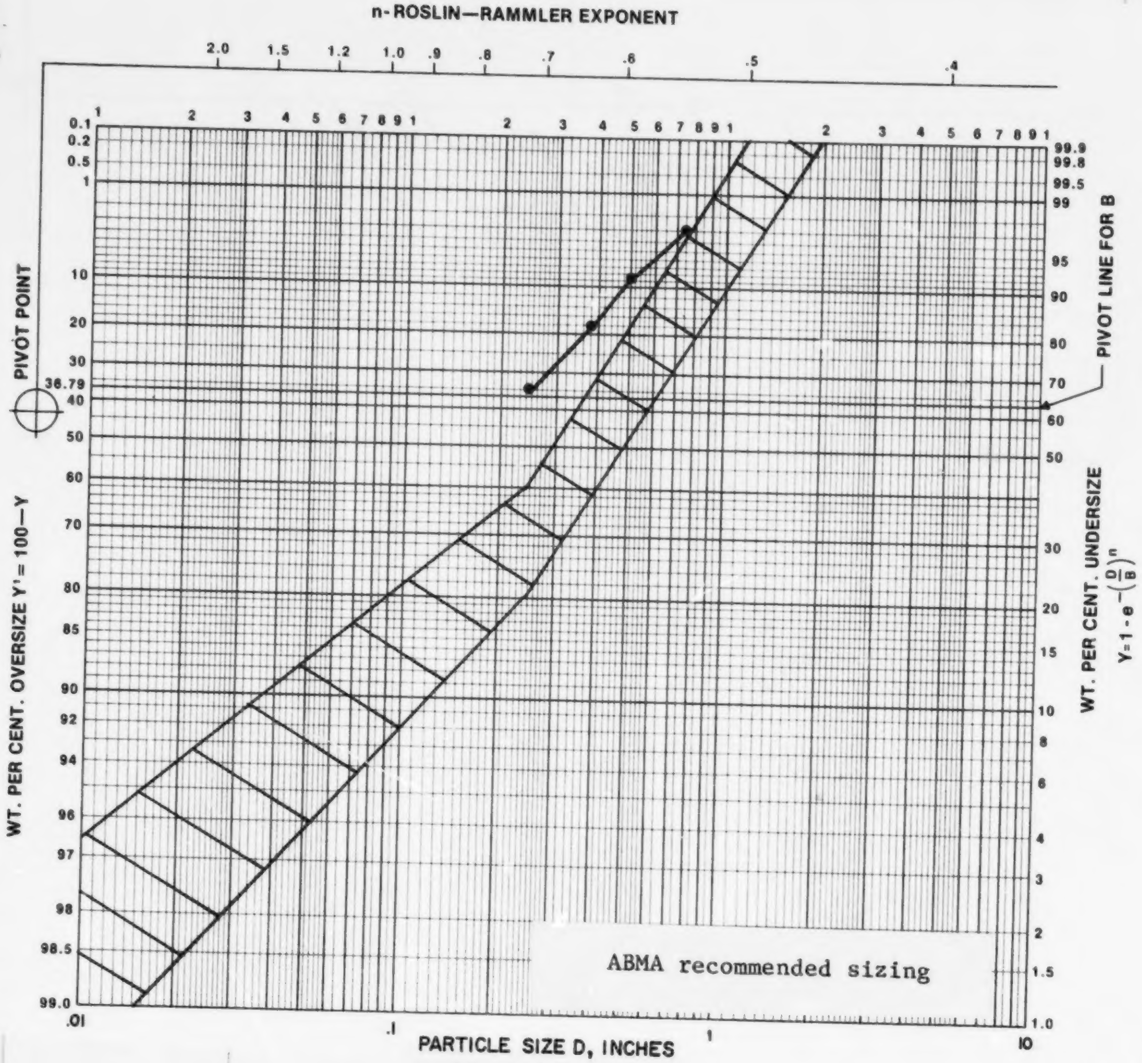

Figure 19. May baseline coal size distribution.

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SECTION 4

PROCEDURES AND EQUIPMENT

BOILER PERFORMANCE

Boiler performance was evaluated using the most appropriate methods available to determine boiler efficiency and fireside corrosion. The flue gas was continuously monitored at the boiler outlet to provide necessary data for calculating the efficiency. To document operational characteristics of the system, the instruments on the boiler control panel were monitored.

Boiler Efficiency

Sufficient data was collected to determine the boiler thermal efficiency by both the input-output method and the heat loss method as described in the ASME Power Test Code PTC 4.1. Lack of precision in the steam metering and feedwater metering systems caused rejection of the input-output efficiency determination. Furthermore, indexing the amount of fuel in the bunker was very difficult resulting in a 10 percent inaccuracy in the rate of fuel usage. Therefore boiler thermal efficiency was determined by the loss (heat balance) method which is not sensitive to either the steam production or heat input rate.

This heat balance efficiency calculation determined boiler efficiency by the equation

$$\text{Efficiency} = 100\left(1 - \frac{\text{heat losses}}{\text{heat inputs}}\right)$$

The values applied to this equation are determined from the following measurements:

1. Fuel properties (to determine heat input)
    - Ultimate analysis
    - Higher heating value
    - Blend ratio by weight
    - Moisture content
    - Average fuel usage rate

2. Flue gas properties (to determine heat loss)
    - Boiler outlet O_2 concentration
    - Economizer outlet gas temperature
    - Fly ash concentration at ESP inlet

3. Ash properties (to determine heat loss)
   Combustibles content of collected ESP fly ash
   Combustibles content of bottom ash
   Multiclone collection rate (if no reinjection)

The heat losses accounted for include the following:

1. Wet flue gas loss--determined from the fuel moisture content, hydrogen content, fuel input rate, and economizer outlet gas temperature. Humidity in the combustion air was neglected.

2. Dry flue gas losses--from fuel input rate, stoichiometric air:fuel ratio, excess air determination, economizer outlet gas temperature. It was assumed that all combustion air was at 70°F.

3. Fly ash losses--unburned combustibles in the collected ESP fly ash.

4. Bottom ash losses--from difference in input ash rate and measured fly ash rate, and unburned combustibles in bottom ash samples.

5. Multiclone collection loss--(when fly ash reinjection was discontinued) based on multiclone collection rate and combustibles content of the collected fly ash.

6. Radiative/convective losses--from ABMA Standard Radiation Loss Chart.

Any other losses were considered negligible or unaffected by fuel type.

Heat input is the product of the fuel feed rate and fuel higher heating values. Other sensible heat credits were neglected.

For details of the calculation, see Data Columns 201 through 269 in Appendix B and Equations 201 through 260 in Appendix C.

Prior to the test, new Toledo Belt Scales were installed at two locations along the coal conveyor system by General Electric. Since these belt scales were calibrated during installation and had a specified accuracy of ±0.25 percent, it was assumed that no further calibration was necessary. However, as testing proceeded, it was noted that each day the amount of fuel weighed into the bunker took 10 to 15 percent longer than predicted to be consumed. When loads of coal were weighed on a truck scale and then weighed on the belt scales, it was found that the belt scales were providing erroneous weights. The magnitude of the error was consistent with the amount that fuel usage was mispredicted. Since this problem was discovered after the completion of testing, correction factors were developed and applied to the data.

Flue Gas Characterization

Concentrations of the major species in the boiler outlet flue gas was monitored. A slipstream of flue gas was extracted and conditioned as described in the emissions characterization section of this chapter. Oxygen was monitored by a Theta Sensors Oxygen analyzer. The electrical signals from this device are directly proportional to the oxygen concentration. Carbon dioxide was measured by a Beckman Model 864 Nondispersive Infrared Spectrophotometer (NDIR). Carbon monoxide was measured by another Beckman Model 864 NDIR. The output signals of all three continuous monitors was recorded on a Leeds & Northrup Multipoint Strip Chart Recorder.

The carbon dioxide concentrations were also monitored between the first two rows of screen tubes directly above the grate. Both sides of the boiler were monitored simultaneously. This simultaneous CO_2 monitoring provided information on the uniformity of the combustion process across the grate.

The high gas temperatures in the screen tube region dictated the use of water cooled probes for withdrawing the samples. This sampled gas was passed through a condenser and moisture trap to protect the instruments. The carbon dioxide concentrations were continuously monitored by two Horiba Mexa 221 nondispersive infrared analyzers. Outputs of these instruments were recorded on another Leeds & Northrup Multipoint Strip Chart Recorder. These gas analyzers had internal sampling pumps.

Calibration of the CO_2 analyzers was performed in accordance with the manufacturer's recommendations. The instruments were zeroed with ambient air and calibrated while injecting a 10 percent carbon dioxide standard supplied by Horiba. Frequent plugging of the water-cooled probes and blinding of the in-line filters greatly reduced the amount of data generated by this system. The results are reported as the difference in CO_2 concentrations between the two sides of the boiler in Appendix B, Column 150.

Boiler Operation

Pertinent boiler operating data was collected every 1/2 hour throughout the daily test period. Typical data collected included: steam production rate and feedwater input rates, relative air flow, temperatures and pressures of the steam and feedwater, and the water level in the steam drum. Also the static pressures throughout the stoker and boiler system were recorded to indicate any abnormal operating conditions in the gas flow path. Flue gas temperatures were monitored in four different places. In two of these locations, the screen tube area and the convective section, type K thermocouples were installed and attached to a third multipoint recorder. Though these thermocouples were uncalibrated and did not account for radiation effects, these readings were adequate to indicate any shifts in gas temperature.

Calibrated vapor pressure thermometers continuously recorded the gas temperatures at the economizer inlet and the economizer outlet. The recording vapor pressure thermometer installed at the economizer outlet was calibrated by the General Electric instruments and controls technicians. This thermometer was used to measure the boiler outlet gas temperature for heat loss calculations.

Using a hand held tachometer and stop watch, the spreader and grate speeds were measured. General observations about the flame color, ash bed depth, and bottom ash appearance were also recorded.

Corrosion Analysis

On the weekends of March 10 & 11, March 17 & 18, and May 12 & 13, the boiler was taken off-line and cooled. Slag specimens were then removed from the furnace walls, screen tubes, and superheater tubes. These specimens were analyzed for their physical and chemical properties and screened for their corrosivity potential. Appendix D is a full report of the test methodology and results of this analysis.

ASH CHARACTERIZATION

Bottom Ash

The bottom ash generation rate was checked by first emptying the bottom ash hoppers in the normal manner (using the pneumatic conveyor system to completely clean out the hoppers). The time was noted, and after 1 to 2 hours the hoppers were again emptied by placing a metal chute in the hopper and transferring the bottom ash manually into an empty dump truck. When the hoppers were again completely empty, the time was noted and the contents of the truck weighed. The weight of the bottom ash collected during that time period was used to verify the bottom ash generation rate calculated by subtracting the fly ash emission rate from the input rate of fuel inerts.

During the ash transfer procedure or normal ash removal operations, ash samples were taken for subsequent physical and chemical analysis. Random shovels full of bottom ash were composited into two 5-gal buckets, one bucket for each side of the boiler. These 5-gal composite samples were split with a Gilson Porta Splitter SP-2 to a 1-gal volume. These 1-gal samples were then taken back to SYSTECH's main laboratory for the chemical and physical analysis.

The 1-gal laboratory sample of bottom ash was mixed and quartered. One half of the sample was returned to the original sample container and kept as a record sample. One quarter of the sample was ground to 0.5 mm size in a Model No. 4 Wiley Mill. Half of this ground sample was retained as a record sample, the other half was sent to Gilbert Associates Laboratory for further chemical analysis. Approximately a 1-g sample of the ground bottom ash was dried in a drying oven for 1 hr at 103°C, cooled in a desiccator, and weighed. This dried, weighed sample was then ignited in a muffle furnace which was brought to 750°C and maintained at that temperature for 1 hr. The sample was then cooled, desiccated, and reweighed to the nearest 0.1 mg. The weight loss of this sample was reported as percent combustible matter. The quarter of the sample which was not ground was subjected to the same size distribution and particle density analysis as the coal and fuel blend samples as described in the Fuel Analysis Section.

Boiler Outlet Particulate

In order to characterize the particulate mass emission rate upstream of the multiclone dust collectors during fly ash reinjection, a boiler outlet particulate sampling method was devised. Sampling had to be performed in the region of the boiler shown in Figure 20. At this outlet of the convective section of the boiler, the flue gas flows downward past the mud drum. The "skimmer baffle" constricts the cross section and causes an acceleration in the gas velocity before it changes direction to flow laterally into the multiclones.

Initially, sampling was attempted using a ceramic thimble type sampler. The procedure was difficult, and the gas flow conditions were unsuitable for sampling. When the results of tests conducted by this method could not be reproduced, the ceramic thimble technique was abandoned.

A system was designed and constructed to sample the particulate through a slot across the throat of the skimmer baffle opening. This sampling head is shown in Figure 21. Figure 22 is a schematic of the sampling system attached to this head.

The sampling rate was determined by calculating the flue gas flow rate from the fuel feed rate and air-to-fuel ratio. The average velocity at the throat of the skimmer baffle was determined for the conditions of the flue gas at that location. Based upon these calculations, the sampling system was adjusted to collect a proportionate flue gas sample.

This sampling system was used in the May blend and coal baseline tests only. Sampling runs of about 2 minutes were possible before the filter would blind. This sampling procedure was replicated about 15 times per day. The combination of cyclone capture and high volume filter capture provided sufficient sample for mass rate, particle size characterization, and chemical properties determinations.

Multiclone Fly Ash

To establish a relative measure of the multiclone collection rate, two of the four multiclone fly ash hoppers were modified by welding 1-ft-long-vertical sections of 1 1/2-in. pipe to the hopper near its bottom. A gate valve was installed near the top of the pipe section, and a cap was threaded onto the pipe bottom. In operation the gate valve was first opened and the sampling pipe emptied. The cap was then replaced and the time noted. Approximately 30 minutes later the valve was closed, the exact time noted, and the fly ash which had collected during that time was transferred to a sample bottle for later analysis. The weight of the fly ash collected over this time period was intended to be a relative measure of the multiclone collection rate for that boiler loading and fuel blend condition. The fly ash sample was saved and subjected to the same analysis described for bottom ash in the previous sections.

In normal operation the fly ash collected by the multiclone dust collector is reinjected with the rear overfire air. To assess the impact

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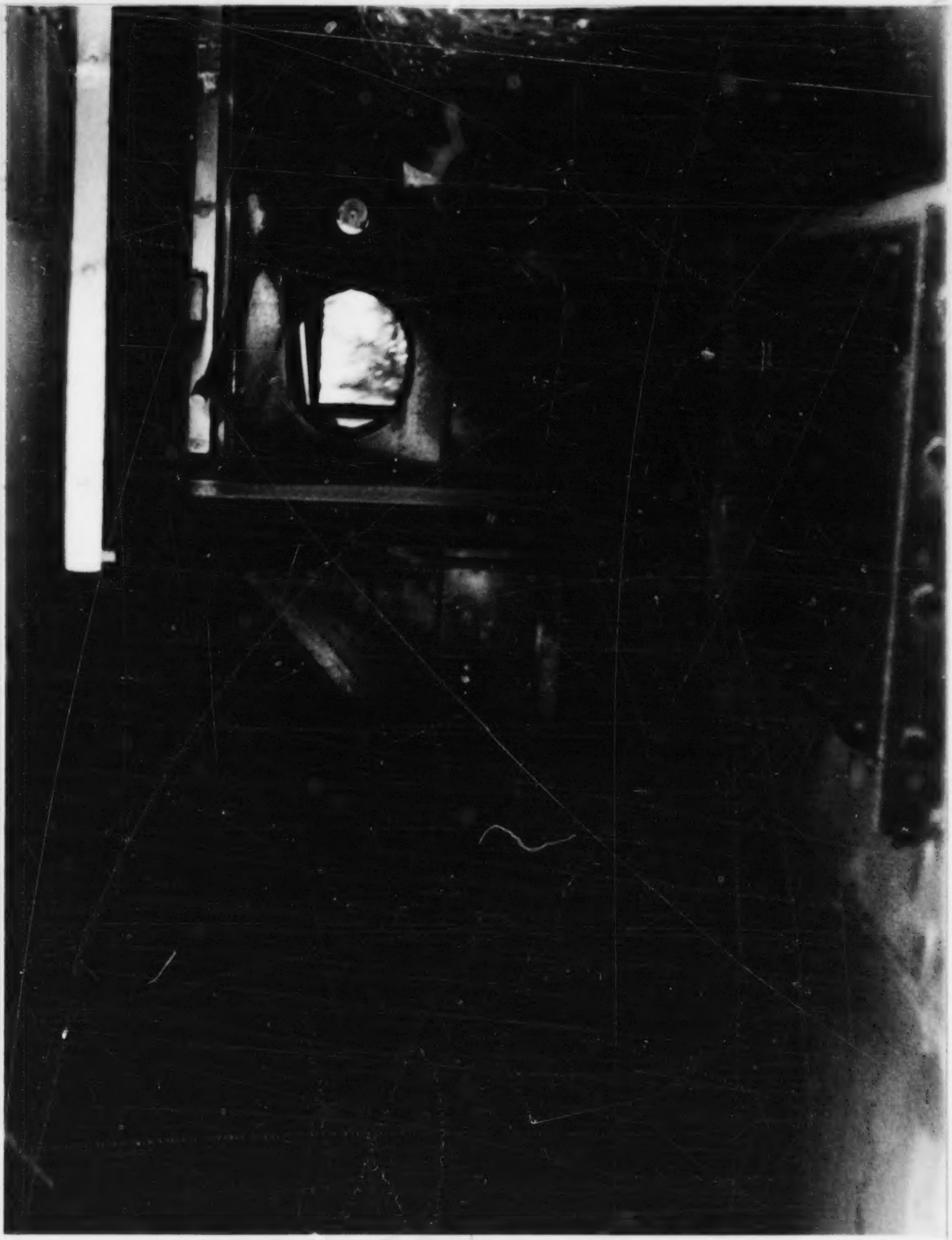

Figure 20. Boiler outlet sampling region.

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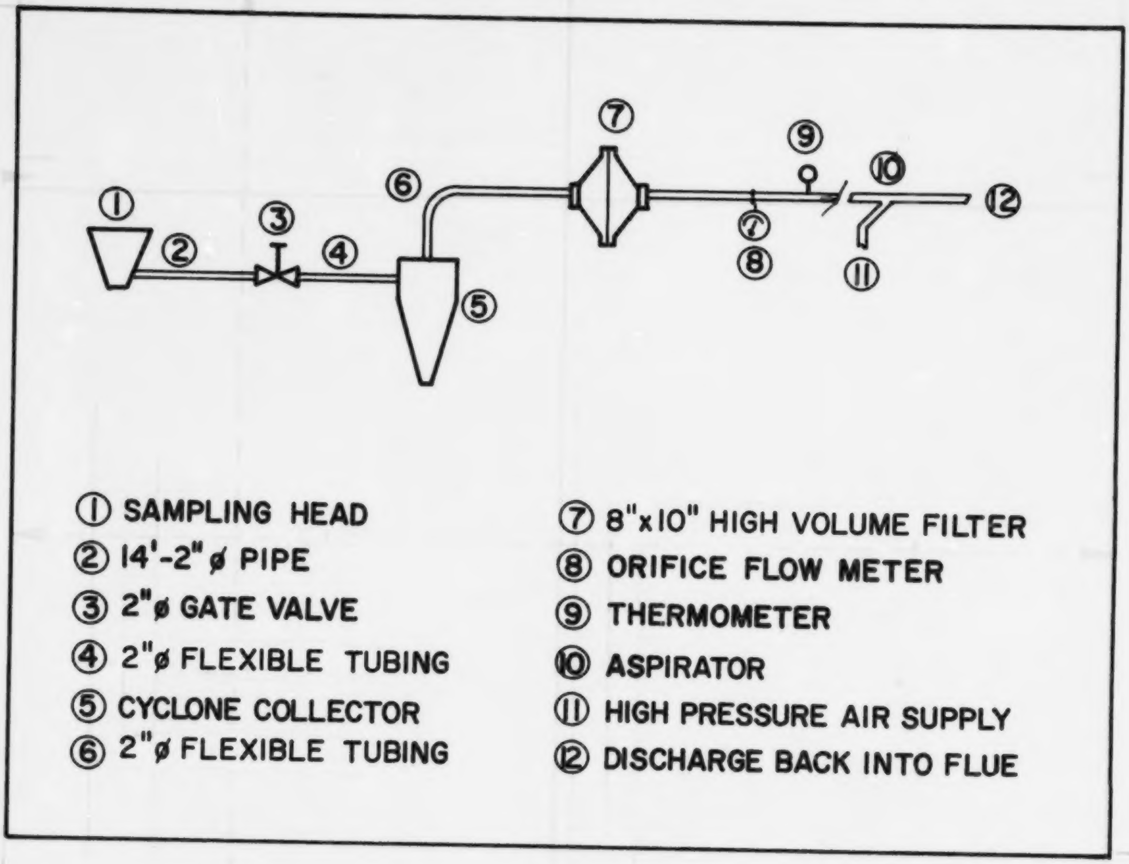
Figure 21. Boiler outlet fly ash sampling head.

this practice has on particulate mass emissions while firing dRDF, the reinjection system was modified. A bypass system was installed that permitted the optional collection or reinjection of fly ash. As indicated in the April and May schedules, testing was conducted without fly ash reinjection on 4 days. On all four occasions the boiler was operated at full load, with either coal-only or 1:2 Teledyne blend.

ESP Fly Ash

Fly ash samples from the ESP were obtained from ports installed near the base of the fly ash collection hoppers just above the pneumatic conveying system. Since these hoppers were kept under a negative pressure, the cap was removed from these ports so fly ash would be drawn back into the hopper, thus clearing the sampling port of fly ash which may have accumulated there for some time. When a sample bottle was placed against the edge of the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① SAMPLING HEAD
② 14'-2"ø PIPE
③ 2"ø GATE VALVE
④ 2"ø FLEXIBLE TUBING
⑤ CYCLONE COLLECTOR
⑥ 2"ø FLEXIBLE TUBING
⑦ 8"x10" HIGH VOLUME FILTER
⑧ ORIFICE FLOW METER
⑨ THERMOMETER
⑩ ASPIRATOR
⑪ HIGH PRESSURE AIR SUPPLY
⑫ DISCHARGE BACK INTO FLUE

Figure 22. Boiler outlet particulate sampling system.

sampling port, the air flow through the port was cut off so the fly ash in the hopper could fall down into the sample bottle. Fly ash samples were taken twice daily from each of the two ESP fly ash collection hoppers. These samples were subjected to the same analysis as bottom ash.

FUEL CHARACTERIZATION

Fuel Sampling

There were three types of fuel samples taken during the test period: dRDF prior to blending, coal prior to blending, and blended fuel as burned. The dRDF pellets were sampled at the ends of belt conveyors (see Figure 23) prior to blending with coal and prior to transfer to the coal bunker. A 5-gal bucket was swung into the free-falling pellet stream at random intervals during the bunker loading operation. Utilization of such a procedure

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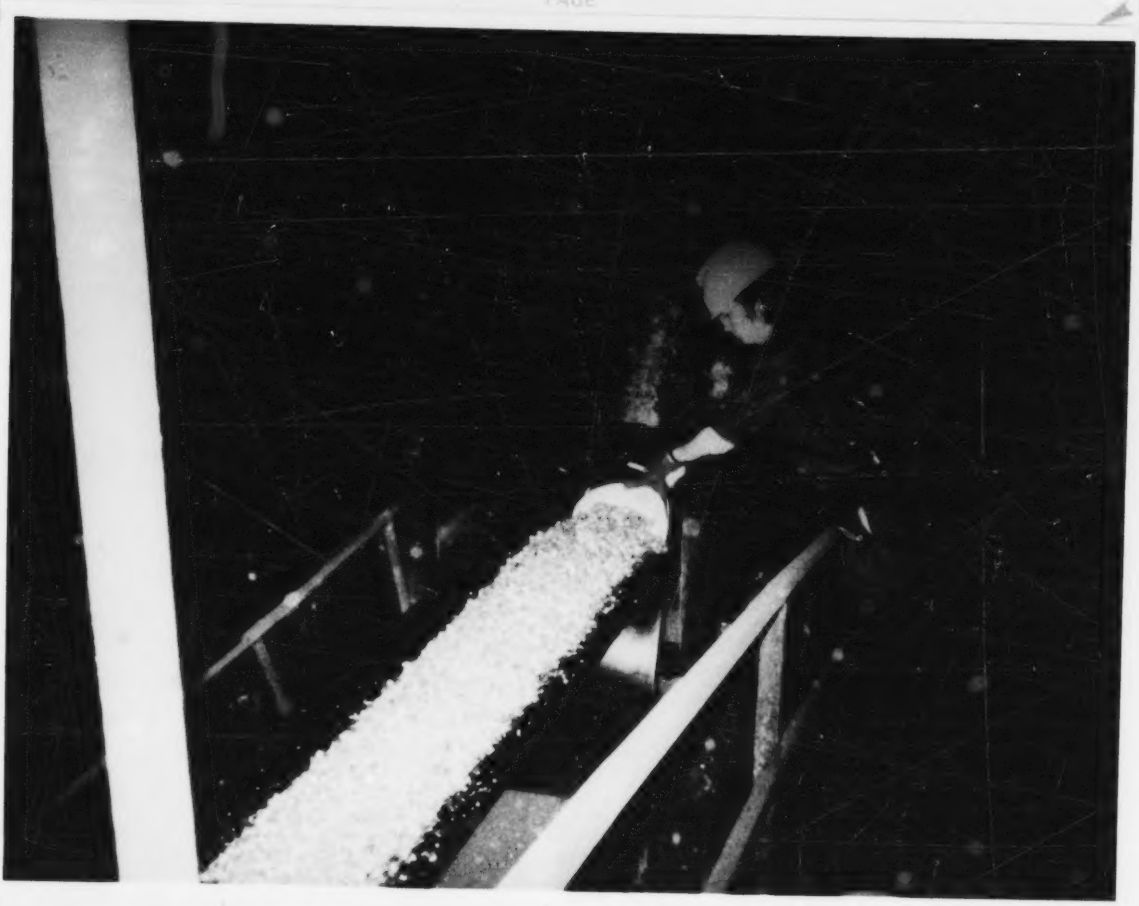

Figure 23. Fuel sampling from end of belt conveyor.

resulted in the collection of a series of 1- to 2-gal discrete samples. A total composite sample of 15 to 20 gal of pellets was accumulated during each sampling period. This composite sample was split with a Gilson Porta (riffle-type) Splitter (SP-2) to a 1-gal laboratory sample which was returned to SYSTECH's main laboratory for analysis. The coal was sampled at the vibratory feeder as it transferred coal onto the conveyor belt. The sampling and compositing techniques were the same for coal as those used for pellets.

Fuel as burned was collected from all six coal stoker hoppers. This fuel was a blend of pellets and coal. During the coal baseline testing all coal samples were collected at the boiler. Approximately a 2-lb sample was taken from each of the six stokers every hour during the test periods. These hourly samples were sealed to protect against moisture loss and stored until the end of the day at which time they were composited and split to a 5-gal laboratory sample which was retained for analysis.

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Fuel Analysis

The laboratory samples of coal and fuel blends were quartered to yield approximately a 2-ℓ sample. This sample was placed on a tared metal tray, weighed to the nearest 0.1 g, and placed in a drying oven which was set at approximately 40°C for 24 hours. The dried sample was then reweighed and the weight loss calculated to yield the air dried moisture. This sample was then mixed and split into two equal components.

One component was passed through a Model No. 4 Wiley Mill which was equipped with a 0.5-mm screen. Approximately a 1-g sample of this milled material was then analyzed for residual moisture by placing it in a tared crucible and heating it in a drying oven for 1 hr at 103°C. The sample was then cooled in a desiccator and reweighed to the nearest 0.1 mg and the weight loss calculated to yield residual moisture content. The remainder of the milled sample was mixed and split into two components. One component was saved as a record sample, and the other component was shipped to Gilbert Associates Laboratory for ultimate and proximate analysis.

The dried sample component which was not milled was then placed in a set of Tyler standard sieves, which included a 1-in., a 3/4-in., a 1/2-in., and a 3/8-in. sieve. These sieves were then placed on a Model RX-24 Tyler Portable Sieve Shaker. After shaking for 2 minutes, the sieve set was rotated 180° and shaken for another 2 minutes. The weight of each size fraction was then determined to the nearest 0.1 g.

Densified refuse derived fuel was analyzed in a different manner. The entire 1-gal laboratory pellet sample was mixed and halved and placed on two tared metal trays and weighed to the nearest 0.1 g. These trays were placed in a drying oven set at approximately 40°C for 24 hours. The air dried moisture loss was then determined and one of the trays of pellets returned to the original sample container to be maintained as a record sample. Experience has shown that a record sample retained with the as-received moisture content has a very high risk of turning into a gelatinous bio-mass which is of little use. Biological activity is inhibited in the dried sample and the integrity of the sample is thus retained. The other tray of dry pellets was further mixed and halved. Half of the pellets were milled to a 0.5 mm screen size. The other half of the pellets were retained for size distribution and particle density analysis. The pellet sample passing through the Wiley Mill was mixed and again halved. One half of that sample was sent to Gilbert Associates Laboratories for further chemical analysis, while the other half was retained as a record sample of the processed pellets.

The residual moisture of the air dried pellets was determined by taking a 1-g portion and placing this portion in a tared crucible. The crucible was placed in a drying oven at 103°C for 1 hour. The sample was cooled in a desiccator and then reweighed to the nearest 0.1 mg. This dried sample was analyzed for its combustible content by igniting it in a muffle furnace for 1 hr at 750°C. The sample was then cooled in a desiccator and reweighed. The weight loss was reported as percent combustible material. The weight remaining was reported as percent ash.

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The procedures used to determine the pellet length distribution and the particle density are modifications of those used by NCRR. A portion of the dried whole pellets was placed on a 3/8-in. sieve and the sieve loaded onto a Model RX24 Tyler Portable Sieve Shaker. The shaker was operated for 2 minutes and the sieve rotated 180° and shaken for another 2 minutes. The material passing through the 3/8-in. sieve was reported as the percent fines of the sample. The remaining pellets which were greater than 3/8 in. were passed through a Gilson Porta Splitter Model SP-2 until approximately 20 pellets were separated. These 20 pellets were measured for length and diameter with a vernier caliper to the nearest 0.1 cm. The weight of those 20 pellets was measured, the volume calculated, and the pellet density determined. The 20 pellets were then remixed with the rest of the pellets and the entire procedure repeated twice more. The results of these three determinations were then averaged to yield the reported size distribution.

Material Handling

The material handling characteristics of dRDF were evaluated through observation. Photographic coverage of the fuel handling process is provided in the Results Section.

EMISSIONS TEST PROCEDURES

Particulate Emissions

Particulate emissions were measured twice daily upstream of the electrostatic precipitator. To measure precipitator efficiency during periods when the boiler was operated at capacity, simultaneous measurements of particulate concentrations were made both upstream and downstream of the electrostatic precipitator. Figure 24 shows the sampling port locations.

Each particulate determination consisted of a 2-hour isokinetic sampling test traversing 30 points of a 5 × 6 matrix of centroids across the inlet and/or outlet duct. The isokinetic sampling tests were conducted according to EPA Reference Method 5 which is published in the Federal Register 42FR41754, August 18, 1977. The only modifications to the standard Method 5 test procedure involved replacement of the distilled water in the first impinger with a 10 percent H_2O_2 solution to capture SO_x, chlorides, and fluorides. Also, a pyrex cyclone was used in the oven upstream of the glass fiber filter. Figure 25 is a schematic of the EPA Method 5 sampling train setup.

Particulate size distribution was determined in situ with a Model 1500 Inertial Cascade Impactor manufactured by Meteorology Research Inc. Figure 26 illustrates the cascade impactor system. Particulate size analysis was performed at the ESP inlet twice daily. On days when the boiler was operating at full capacity, particulate size analysis was performed at the ESP outlet and inlet simultaneously. The cascade impactors were operated according to manufacturer's instructions.

Aluminum collection plates covered with Apiezon H grease were used in the inertial cascade impactor. The greased plates were baked at 400°F for 2 hours before tare weighing. This baking eliminated volatiles in the grease

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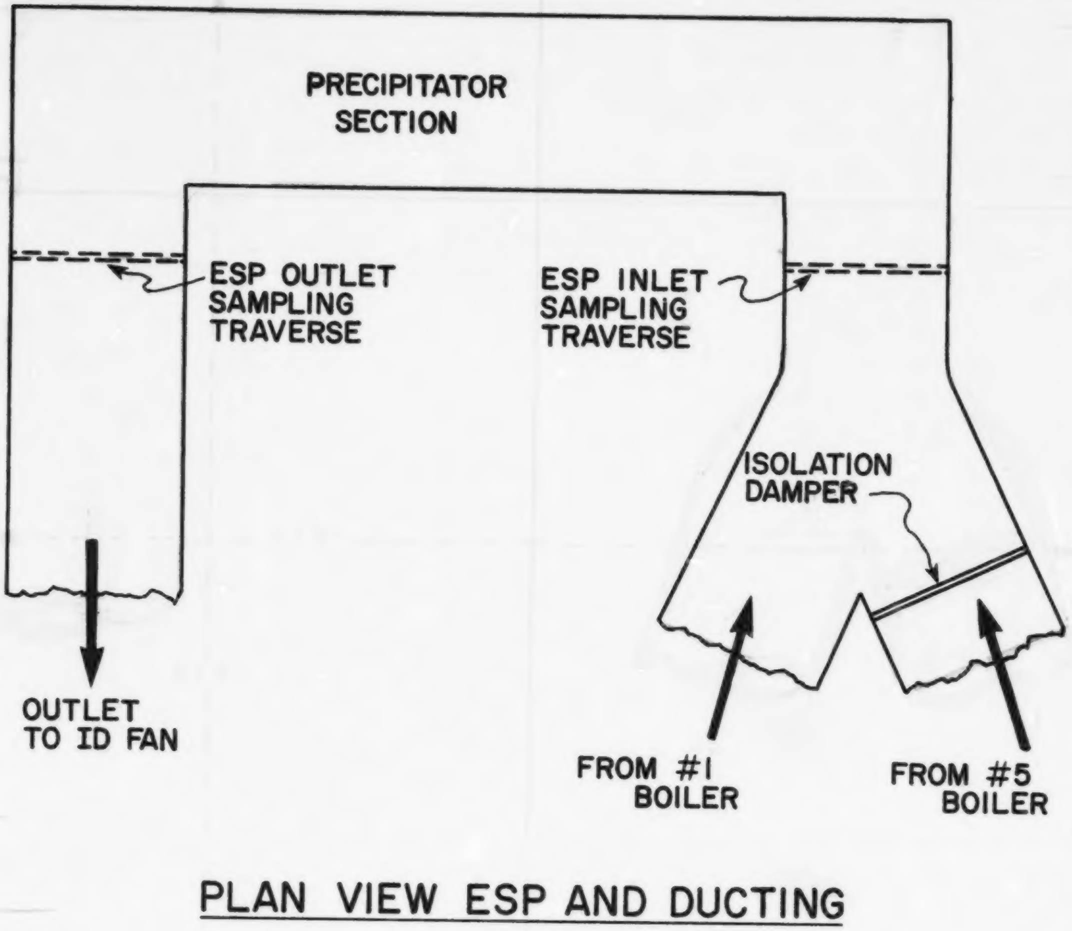
PRECIPITATOR SECTION
ESP OUTLET SAMPLING TRAVERSE
ESP INLET SAMPLING TRAVERSE
ISOLATION DAMPER
OUTLET TO ID FAN
FROM #1 BOILER
FROM #5 BOILER
PLAN VIEW ESP AND DUCTING

Figure 24. Particulate sampling locations of the ESP.

which otherwise might evaporate during the sampling and affect the weight data. The cascade impactor divided the collected particulates by size into seven ranges between .5 and 50 μm.

In situ resistivity measurements of the particulate at the ESP inlet were attempted through the use of a Wahlco Resistivity Probe. Repeated malfunctions of this probe resulted in very little useful data being collected. As a result, samples of the fly ash collected by the ESP were submitted for laboratory resistivity analysis by ASME PTC 28 procedure.

To interpret the ESP efficiency results, electrical characteristics of the ESP were detected by instruments on the boiler control panel. Readings of

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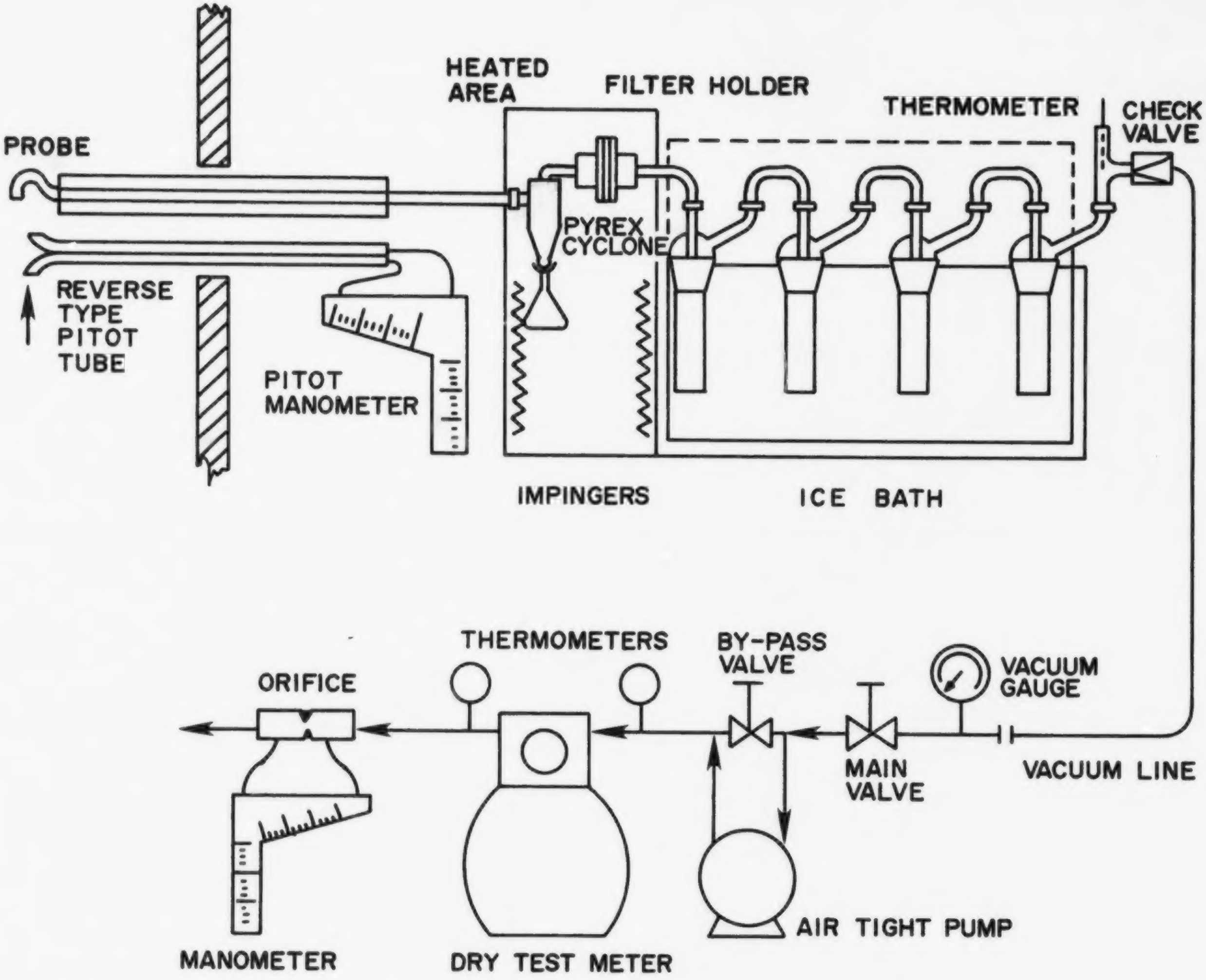
PROBE
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PITOT MANOMETER
HEATED AREA
FILTER HOLDER
PYREX CYCLONE
THERMOMETER
CHECK VALVE
IMPINGERS
ICE BATH
VACUUM LINE
VACUUM GAUGE
MAIN VALVE
BY-PASS VALVE
AIR TIGHT PUMP
THERMOMETERS
DRY TEST METER
ORIFICE
MANOMETER

Figure 25. Schematic of EPA Method 5 sampling train setup.

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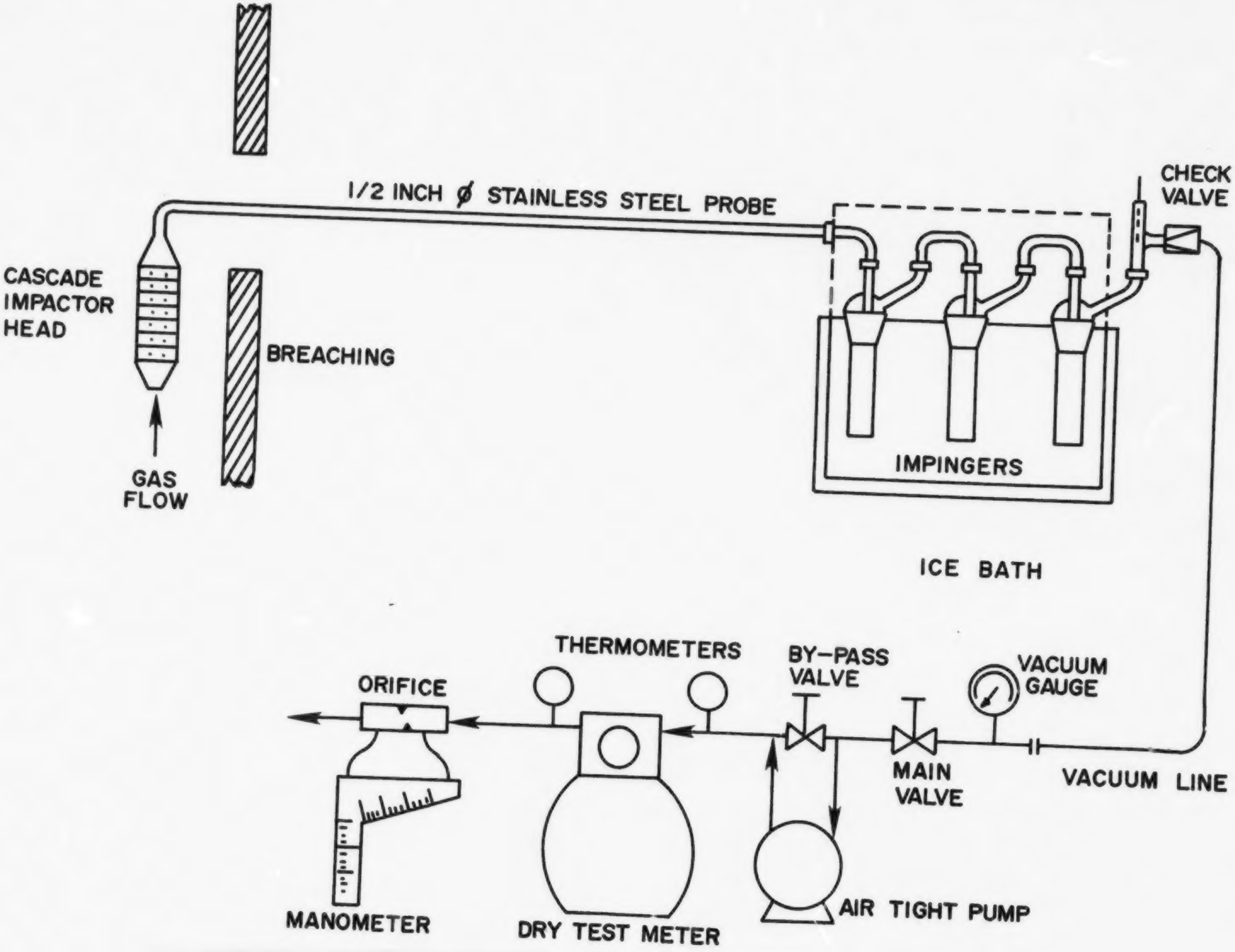
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GAS FLOW
IMPINGERS
ICE BATH
THERMOMETERS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
VACUUM LINE
MANOMETER
DRY TEST METER
AIR TIGHT PUMP

Figure 26. Schematic of MRI cascade impactor sampling train setup.

these instruments were recorded with the 1/2-hour boiler data collection. These readings included the primary voltage and current of each ESP section, the secondary current in each field, and the spark rate of each section.

Method 5 particulate samples were analyzed for lead, zinc, cadmium, chromium, and beryllium. The particulate samples were digested in hydrochloric and nitric acid. All analysis was performed using a Perkin Elmer Model 360 Atomic Absorption Spectrometer.

Gaseous Emissions

Boiler exhaust gases were continuously monitored and recorded while sampling from either of two locations, the boiler outlet and the electrostatic precipitator (ESP) outlet (see Figure 1). The gases which were monitored included oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur oxides (SO_x). The monitoring at the boiler outlet was accomplished to provide a characterization of the combustion process. Gaseous emissions to the atmosphere were monitored at the outlet of the ESP. By comparing ESP outlet results to the boiler outlet results, the dilution of the gases due to the infiltration of ambient air into the ducting was determined. The majority of the monitoring effort was conducted at the boiler outlet. To provide information for the particulate emission calculations, gas composition at the ESP outlet was monitored while the Method 5 particulate tests were being conducted.

The gas samples were collected via 1/2-in. diameter, 8 ft long, stainless steel probes incorporating sintered metal filters manufactured by Paul Trinity Corporation. The probe used at the boiler outlet was constructed so that it could be traversed across an 8-ft depth of the boiler outlet duct to detect stratification. The probe access port at the boiler outlet was located on the side of the boiler approximately 6 in. from the back wall of the boiler outlet duct. The probe at the ESP outlet was approximately 2 ft long and was located in an access port near the sampling ports through which the Method 5 particulate tests were conducted.

Preliminary sampling was performed to determine the proper insertion depth for each probe. With the boiler operating at constant load and fan settings, the probes were traversed from the port inward while monitoring CO_2 and O_2 concentrations. The probes were then fixed at a depth well beyond the stratification and dilution effects of the wall.

To protect the continuous monitors from moisture, each sampling probe was connected to a condensor to remove the moisture from the sample stream. Each condenser consisted of a 6-ft-long, 1/4-in. stainless steel tube coiled and connected to a 250-cc polyethylene condensate collection bottle. The coil and collection bottle was placed in an insulated 5-gal container. The 5-gal container was kept filled with sufficient ice water to cover the coil and collection bottle. From the condensor the sample was drawn through a heated 3/4-in.-diameter teflon tube. This tube transported the sample to the mobile laboratory (often located at distances of 50 to 150 ft from the sampling point). Inside the mobile laboratory a teflon diaphragm pump served as the prime mover of the entire sampling system. On the pressure side of the pump a stainless steel manifold system controlled and distributed the sample to the various continuous monitors. Calibration gases for the continuous monitors were also plumbed through the manifold system. To optimize the response of the monitoring system, the diaphragm pump was operated at its capacity of 2 to 3 ℓ/min. Excess sample was vented to the atmosphere outside the mobile laboratory. At this flow rate the sample response was about 2 minutes.

Sulfur dioxide levels in the flue gas were determined by two different techniques. The reported data was measured by a continuous monitor manufactured by Theta Sensor, Inc. This electrochemical cell analyzer was calibrated with a 1500 ppm SO_2 gas supplied by Airco Products, Specialty Gases Division.

A second technique was employed to provide redundancy and verification for the continuous monitor. In this additional method wet chemistry determinations were used to analyze the sulfur level in the first impinger of the EPA Method 5 train. A 10 percent hydrogen peroxide/water solution was placed in the impinger during the Method 5 test. This solution was then titrated with barium perchlorate to yield a measure of the SO_x scrubbed from the flue gas by the impinger.

The wet chemistry method measures total SO_2 and SO_3 while the continuous monitor measures SO_2 only. Since the SO_3 concentration is typically an order of magnitude less than the SO_2 concentration in a flue gas stream, the comparison of the results is considered to be valid.

Oxides of nitrogen were sampled at the outlet of the electrostatic precipitator in accordance with EPA Method 7 as described in the Code of Federal Regulations Part 40, Appendix A. The samples were drawn through an 18-in.-long, 1/4-in.-OD stainless steel probe inserted through a drilled port cap. The probe was located in the center Method 5 sampling port. Three replicate samples were taken for each measurement and averaged to yield one reported value.

NO_x was also measured by an electrochemical cell continuous monitor. However, frequent difficulties were encountered in maintaining acceptable response and calibration characteristics with this monitor. Therefore, results from the continuous NO_x monitor were not used.

Combustion gases from the boiler outlet were analyzed for total hydrocarbons. A gas chromatograph manufactured by Analytical Instrument Development, Inc., was outfitted with a flame ionization detector and used for this analysis. The sample delivered to the GC was a slip stream of the conditioned combustion gases from the continuous monitoring system. The gas chromatograph was operated in a totalizing mode and calibrated with methane standards. There was some concern that hydrocarbons were being scrubbed out of the gas stream by the condenser system. To test this possibility, gas samples were drawn directly into collapsible containers at the boiler outlet by means of a hand squeeze bulb. This unconditioned gas sample was then injected directly into the gas chromatograph. The conditioned and unconditioned samples both gave the same results, thus validating the use of the gas conditioning system in the hydrocarbon measurement.

The combustion gases were analyzed for phosgene content at the boiler outlet with a National Dräger multigas detector using phosgene detection tubes. The detection tubes used had a minimum detection limit of .25 ppm. No phosgene was detected even after passing five times the prescribed gas volume through the detection tube.

With each particulate mass flux measurement, the chloride and fluoride concentrations in the flue gas were determined. The hydrogen peroxide solution from the first impinger of the EPA Method 5 train was analyzed with specific ion electrodes manufactured by Orion Research, Inc.

Before using the chloride electrode, an aliquot of the hydrogen peroxide solution was prepared with an ionic strength adjuster of sodium nitrate to provide a constant background ionic strength.

The aliquots analyzed with the fluoride electrode were treated with a mixture of glacial acetic acid, sodium chloride, and CDTA to adjust the ionic background strength. Sodium hydroxide was used to adjust the aliquot to a pH between 5.0 and 5.5.

The O_2, CO_2, NO_x, SO_2, and CO were measured by continuous monitors. Continuous monitoring instruments were calibrated in the morning and evening of each test day. The instruments were zeroed with a zero grade nitrogen gas, and the spans were set with the appropriate gas diluted in nitrogen at the approximate ranges that were to be anticipated during the testing. The oxygen standard used was 10 percent, carbon dioxide 10 percent, carbon monoxide 500 ppm, and NO_x and SO_x were both 1500 ppm. These calibration gases were supplied by Airco Products, Specialty Gases Division. The morning calibration procedure consisted of setting the zero on the instruments after purging with nitrogen for approximately 10 minutes. The appropriate standard gases were then released into the instruments, and the equilibration of that instrument was monitored and noted on the strip chart readout. The final adjustment to the proper span setting took place after that period of equilibration. The evening calibration consisted of again delivering the standard gas to each instrument and noting the response given on the recorder. The instruments were then purged with zero grade nitrogen, and the zero response was noted. The differences between the morning and evening calibrations were used to determine a calibration correction factor which was then applied to the data collected that day.

The information from the strip charts was reduced manually by obtaining the actual percent of scale readout at each 5-min interval on the strip chart. The calibration correction factors were applied to the 5-min data points prior to averaging because some of the response curves were not linear. Boiler outlet sample data was reduced to daily averages. Data collected at the ESP outlet were reduced to one average for each Method 5 test period.

SECTION 5

RESULTS

As discussed earlier, the principal objective of the effort described herein was a demonstration test. Thus all testing was performed under typical power plant operating conditions. The realities of plant operation meant that control of the test conditions (i.e., of the predictive or "independent" variables of the experiment) was not as tight as could be expected in a laboratory situation. This gives rise to much apparent scatter in the data with concommitant uncertainty in the results. Such lack of tight control is not unexpected, and in fact, is representative of everyday power plant operation.

BOILER PERFORMANCE

Boiler Efficiency

Boiler efficiency was determined according to the ASME PTC 4.1 heat loss method. As shown in Figure 27, the average boiler efficiency decreases by about 2.5 percent when firing a blend consisting of two volumes of dRDF and one volume of coal. All of the efficiency loss caused by dRDF firing is a result of the increased wet flue gas loss (see Figure 28). This increased loss could be expected because dRDF is a high moisture and high hydrogen fuel.

Dry flue gas losses (Figure 29) were affected by the excess air level but not by the dRDF. As can be seen in Figure 30, wide range of excess air levels were used by the various operators of the test boiler. No studies of the dependences of excess air on fuel type were made. In Table 14 it can be observed that, on a heat specific basis, dRDF requires about the same amount of combustion air as coal.

Densified refuse derived fuel will cause about a 4 to 6 percent increase in total flue gas output per unit heat input. Since most of this increase is moisture, there is no reason for dRDF to increase dry flue gas flow rate.

Economizer outlet temperatures were evenly distributed among the coal only and the dRDF:coal blends over the range of boiler loads tested (Figure 31). Therefore no increase in dry flue gas losses was expected nor detected when firing dRDF.

Other losses such as blowdown and radiative/convective losses were assumed unchanged by fuel type. A small credit due to the sensible heat in the warm dRDF from storage was neglected in this analysis.

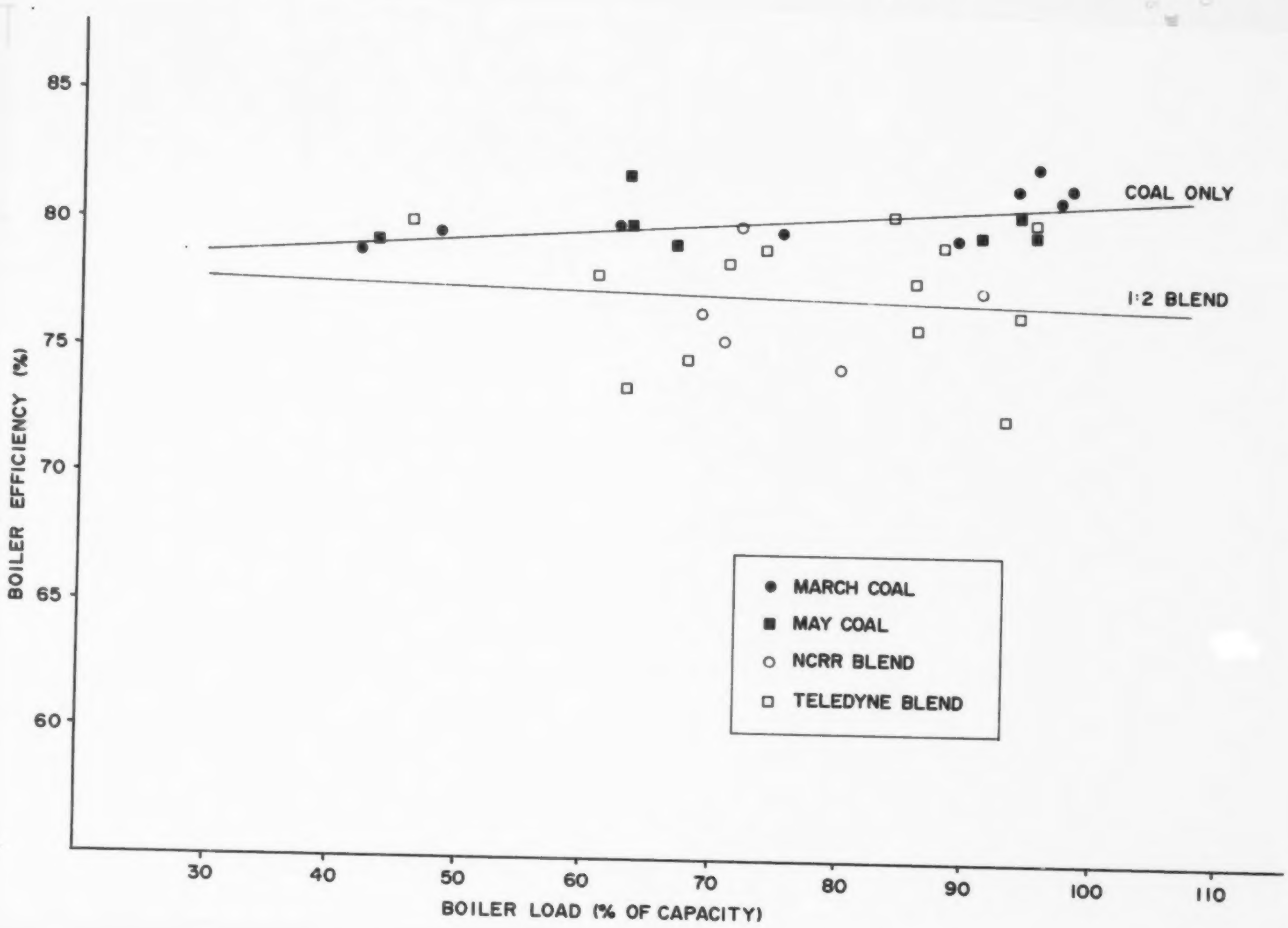

Figure 27. Boiler efficiency.

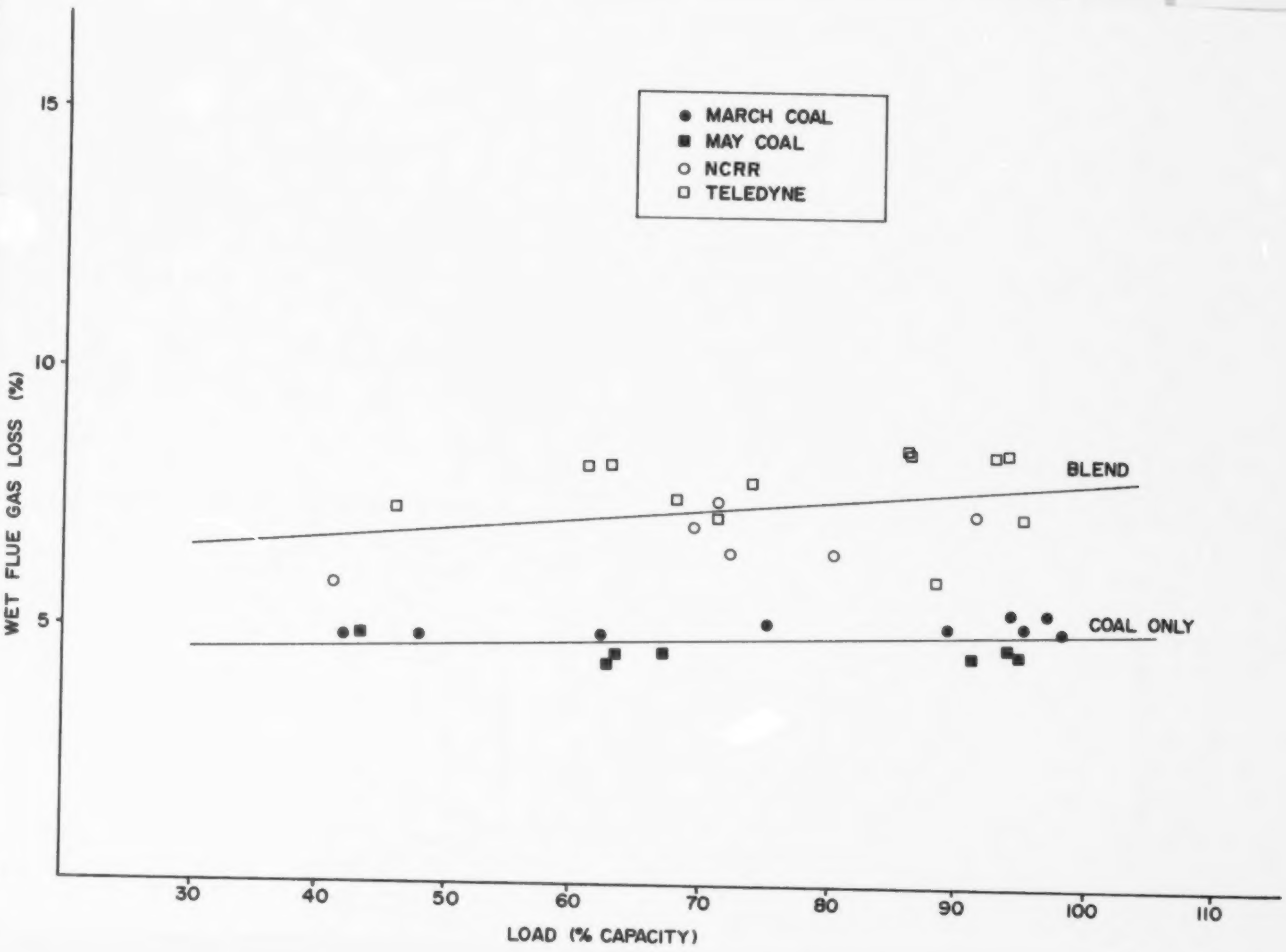

Figure 28. Wet flue gas loss.

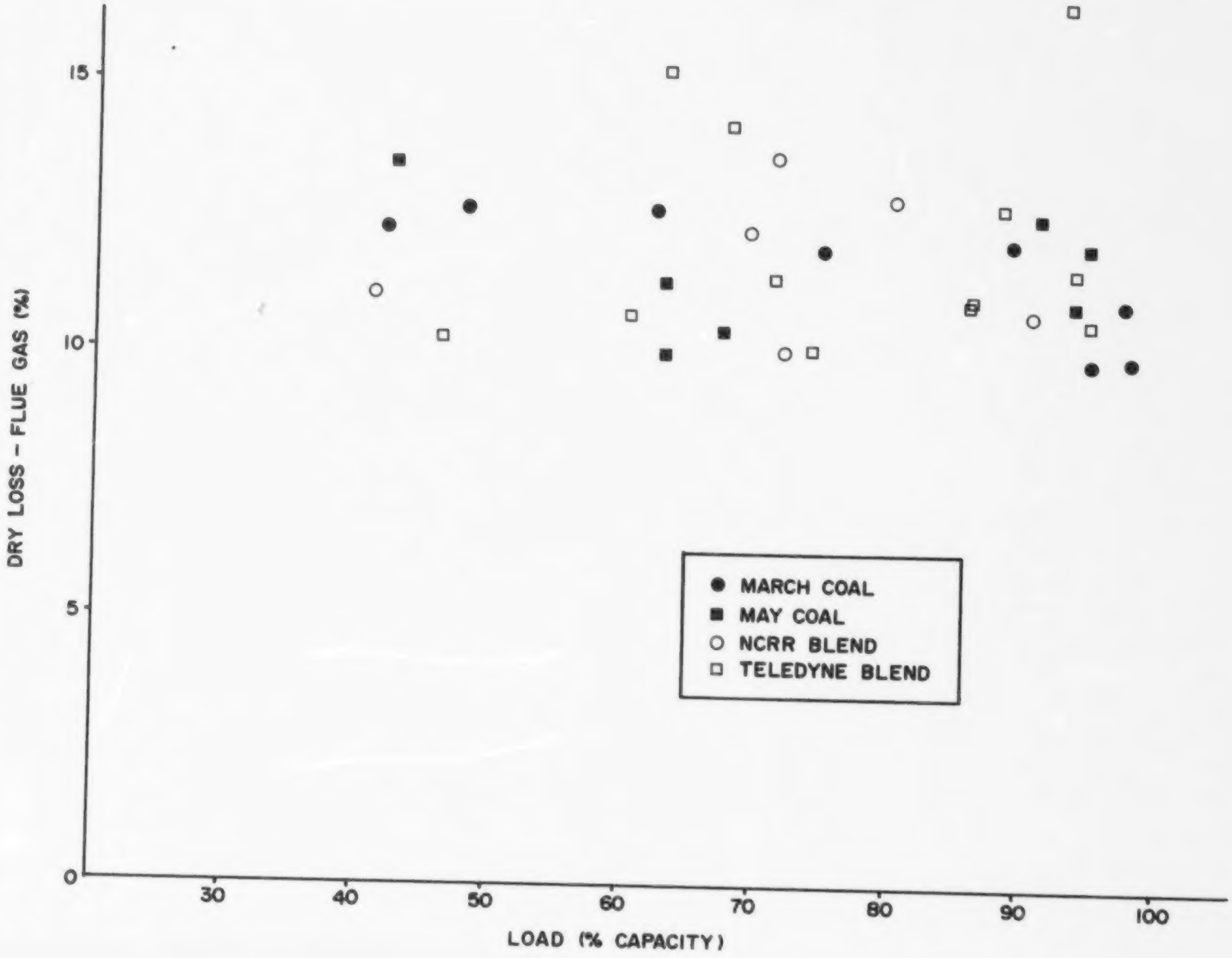

Figure 29. Dry flue gas loss.

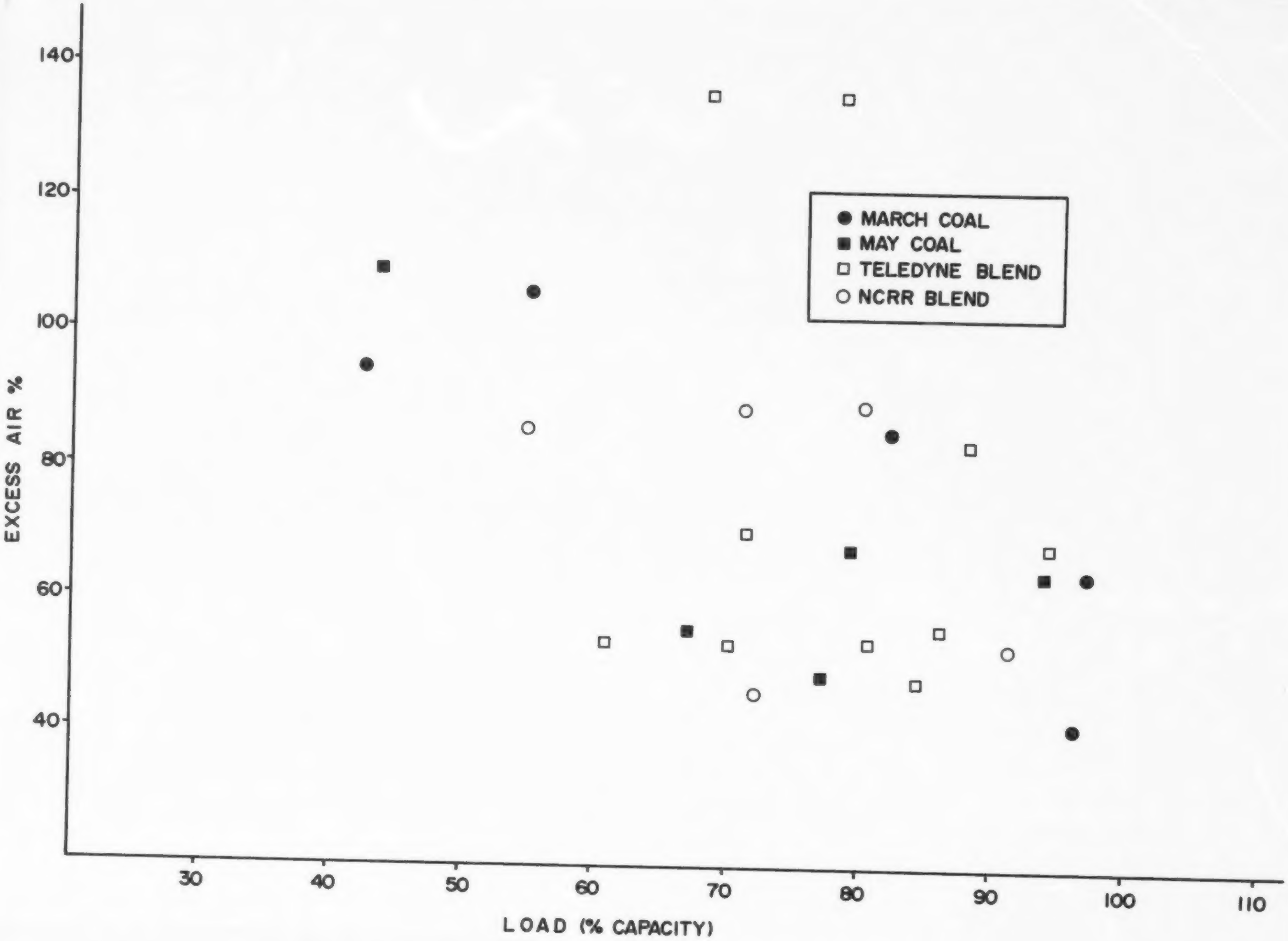

Figure 30. Excess air levels.

TABLE 14. STOICHIOMETRIC COMBUSTION AIR REQUIREMENTS (FUEL ON DRY WEIGHT BASIS)

Fuel	Weight specific (pounds air / pounds fuel)	Heat specific (pounds air / million Btu fuel)
Coal	9.44	766
NCRR pellets	5.30	784
Teledyne pellets	5.95	732
Blend 20 - 30 percent NCRR dRDF	7.75	762
Blend 30 - 40 percent Teledyne dRDF	8.00	754

Heat losses due to uncombusted material in the fly ash appeared to decrease an average of about 0.5 percent when firing dRDF (see Figure 32). However this 0.5 percent decrease was offset by an increase in bottom ash heat losses (see Figure 33). Therefore composite ash losses due to uncombusted materials is unchanged by the substitution of dRDF. All data and calculations used in the boiler efficiency analysis are presented in columns 201 through 272 in Appendices B and C.

Boiler Operation

The boiler was found to be capable of generating steam at its rated capacity of 150,000 lb/hr while firing dRDF at volumetric ratios up to 4 parts dRDF to 1 part coal (51 percent of heat input from dRDF). It should be noted that the boiler apparently is capable of excess capacity because the operators reported generation rates up to 175,000 lb/hr when firing coal.

Five factors that limit the capacity of a steam generator are analyzed in this study. These factors include (1) fan capacity, (2) grate heat release, (3) furnace liberation, (4) heat exchange efficiency, and (5) stoker capacity.

Because of the overdesign characteristic of older steam generators, fan capacity did not limit steam generation capacity while combusting dRDF. To generate 175,000 pounds of steam per hour while firing coal, this unit demonstrated an excess fan capacity of at least 17 percent by volume and weight. Table 15 shows the forced draft and induced draft fan requirements on a per unit heat input basis. As the table indicates, RDF requires

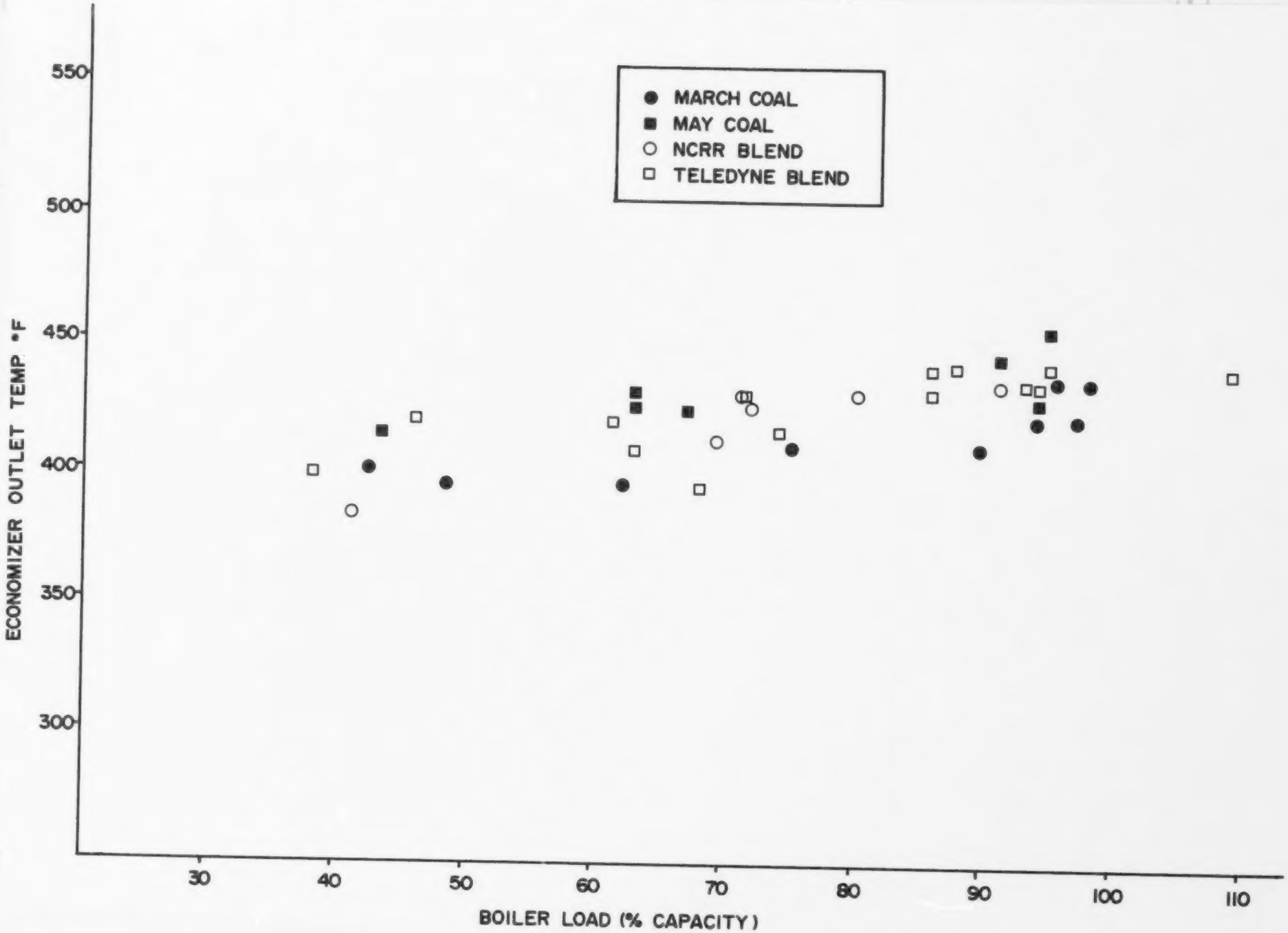

Figure 31. Economizer outlet temperatures.

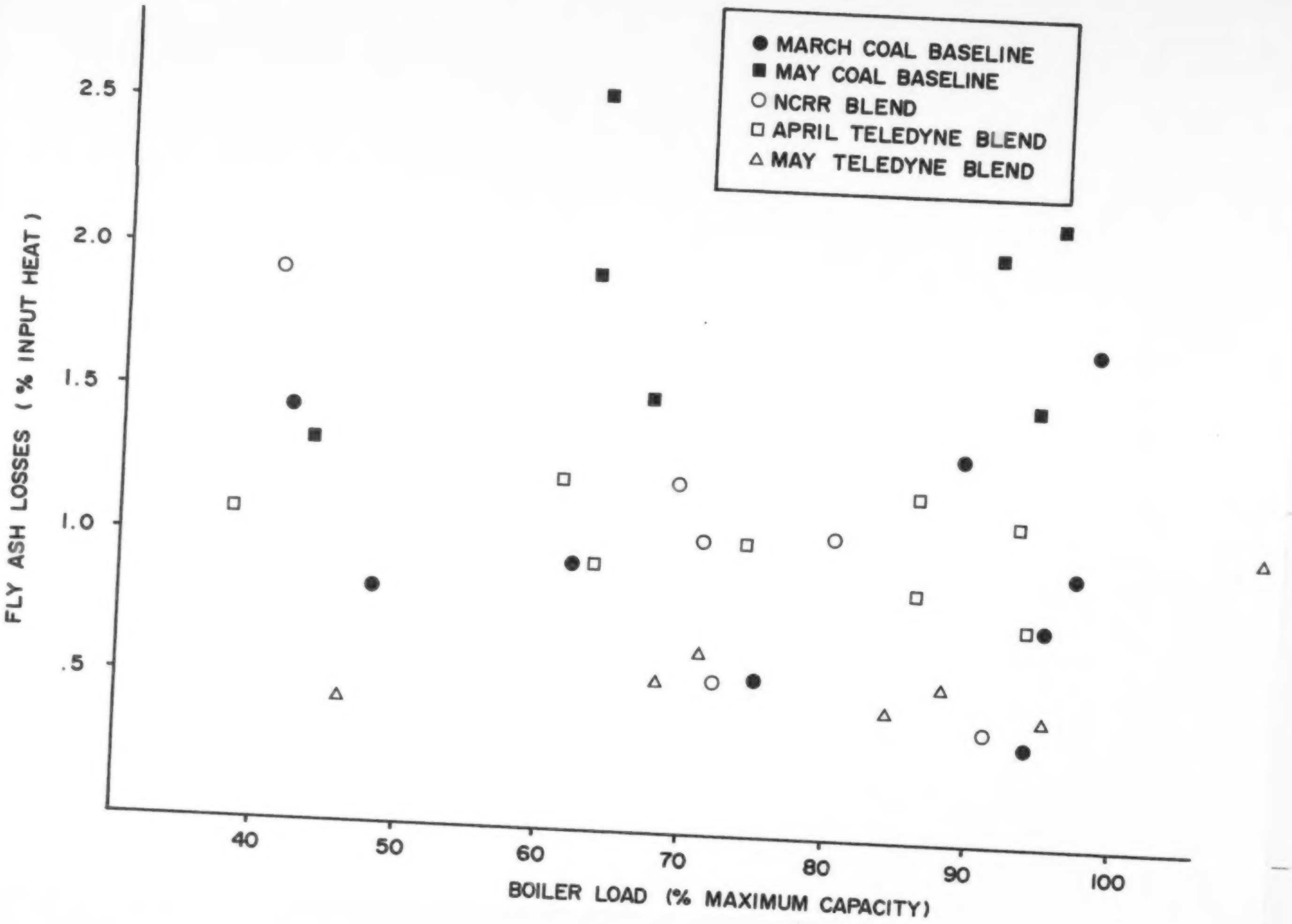

Figure 32. Fly ash heat losses.

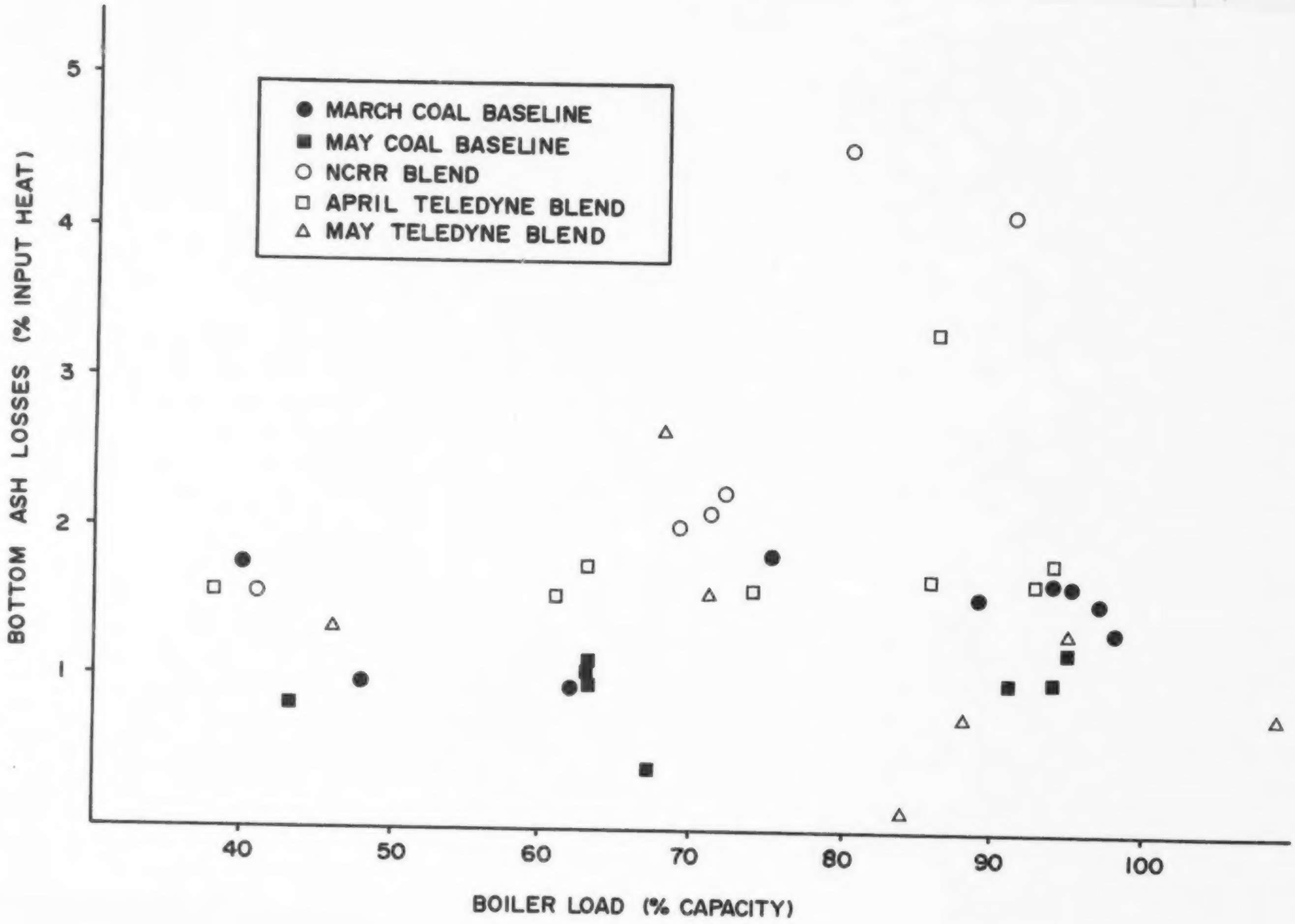

Figure 33. Bottom ash heat losses.

TABLE 15. FAN REQUIREMENTS FOR VARIOUS FUEL BLENDS*

	Coal	50 percent dRDF	dRDF
Combustion air (forced draft)			
lb/10^6 Btu	1,126	1,112	1,099
ft^3/10^6 Btu†	15,020	14,837	14,655
Flue gas (induced draft)			
lb/10^6 Btu	1,199	1,233	1,267
ft^3/10^6 Btu#	26,892	28,304	29,717

* NOTE: At 50 percent excess air, with Teledyne dRDF at 33.7 percent moisture, and average coal at 7 percent moisture.

† At 70°F

# At 450°F

approximately 2.5 percent less combustion air than coal. Therefore, the forced draft fan capacity should not limit boiler capacity while firing dRDF. Since dRDF is higher in volatile matter than coal, it was expected that more overfire air would be required while combusting coal/dRDF blends. However, the ratio of overfire to underfire air was not changed for blend firing, and no increases in carbon monoxide or hydrocarbons were detected in the flue gas. The combustion of dRDF produces 5.5 percent more flue gas by weight than coal. But since much of this additional flue gas is water vapor, this results in 10.5 percent more flue gas volume. Since there was at least 17 percent excess fan capacity, induced draft capacity could not prevent this boiler from operating at 100 percent of its rated steam generation capacity. However on boilers which are not overdesigned, induced draft capacity could become the limiting factor in dRDF use.

The test boiler had a traveling chain grate with 376 ft^2 of fireside surface. At the rated heat input rate of 220 × 10^6 Btu/hr, the grate has a heat release rate of 585,000 Btu/hr/ft^2. With the 2.5 percent reduction in efficiency experienced while firing dRDF, the required grate heat release was increased to 597,000 Btu/hr/ft^2 at rated load. Since the boiler previously demonstrated that 682,000 Btu/hr/ft^2 could be supported by the grate at 175,000 lb/hr of steam and since little increase in combustible materials was found in the bottom ash while firing dRDF blends, grate heat release rate does not appear to be a limiting factor.

The furnace of this steam generator has a rated liberation of 27,900 Btu/hr/ft^3. This is a high liberation rating, especially when firing refuse. Even at full load, while firing dRDF blend and with flame filling the furnace volume, there were no increases in the concentrations of carbon monoxide or hydrocarbons in the flue gases. Therefore, despite the high liberation rating of this furnace, there was sufficient retention of the combustion gases to complete the combustion reaction. Thus, no capacity derating was experienced because of insufficient furnace retention.

Significant deterioration of boiler efficiency can also limit steam generation capacity. But as stated above, a decrease of only about 2.5 percent was measured in boiler efficiency when burning dRDF blends. Since this steam generator has an apparent 17 percent excess capacity, no derating was experienced.

Since dRDF has only about one-forth the heating value of coal per unit volume, and since coal stokers have a volumetric feeding limitation, it was anticipated that considerable derating of the boiler would be caused by the combustion of dRDF. Table 16 shows the heat densities (higher heating

TABLE 16. HEAT DENSITIES OF THE TEST FUELS

Blend	10^6 Btu/ft^3
May baseline coal	.66
March baseline coal	.60
Teledyne dRDF at 23 percent sub.	.41
NCRR dRDF at 25 percent sub.	.36*
Teledyne dRDF at 30 percent sub.	.35
Teledyne dRDF at 50 percent sub.	.33
Minimum density at stoker capacity	.30†
NCRR dRDF at 30 percent moisture	.17

* Could not maintain full load.

† 720 ft^3/hr feeder capacity, 220 MMBtu/hr input.

value ÷ bulk density) of various coal/dRDF blends fired during the tests. The maximum fuel throughput of this spreader stoker system is 720 ft^3/hr. At this volumetric capacity, fuels having heat densities as low as 0.30×10^6 Btu/ft^3 could be fired without derating the boiler. The substitution of dRDF in the range of 23 to 51 percent of total heat input did not result in heat densities below 0.30×10^6 Btu/ft^3. However, during the firing of NCRR-produced pellets at 25 percent of the heat input rate, the boiler could not produce more than 85 percent of its rated steam output.

Inspection of the boiler at the conclusion of this test revealed a large buildup of moist coal and slack of the pusher plate of the spreader. This buildup reduced the volumetric throughput of the spreaders and so the effective minimum acceptable heat density was then greater than the 0.36×10^6 Btu/ft^3 of that blend. This throughput limitation precluded firing at full capacity.

Fuel Bed and Ash Characteristics

While combusting NCRR pellets a skin clinker formed over the entire surface of the fuel bed. However, this clinker remained porous enough to maintain uniform combustion across the grate. Frequent clinkering caused an undetermined loss of combustibles to be bound up in the clinkers. The clinkers also required manual handling and removal from the ash pit (see Figure 34). Ash removal from the pit had to be increased to accommodate the high ash content of the NCRR dRDF:coal blend. The inert fraction of these high ash pellets probably contains a considerable amount of fine glass. Although glass is plastic at bed temperatures, it is still very viscous. In an ash fusion analysis glass would probably appear to have a high softening temperature. As fuel from the spreaders impacted on the ash bed, this glass could deform, thus causing the skin clinker which in turn occasionally caused larger clinkers.

In general the Teledyne pellets burned well and had acceptable concentrations of combustibles in the fly ash. Only minor clinkering occurred at the No. 6 feeder which is located below the bunker fill conveyor end pulley. Fuel fines accumulate above this feeder and cause different combustion characteristics in the region of the grate that this feeder services. This clinkering was actually less than that experienced with coal. The flame above the fuel bed was uniform and bright yellow, with minimal smoking and no apparent holes in the flame pattern. Bottom ash handling was increased, but not as dramatically as with the NCRR pellets. While firing coal only at maximum rated capacity, there were sparklers present in the screen tube section of the furnace. But when firing blend at full load, these sparklers increased and puffs of flame were observed in the screen tube section (see Figure 35). Small globules of slag accumulated on the tubes but immediately melted and sloughed off.

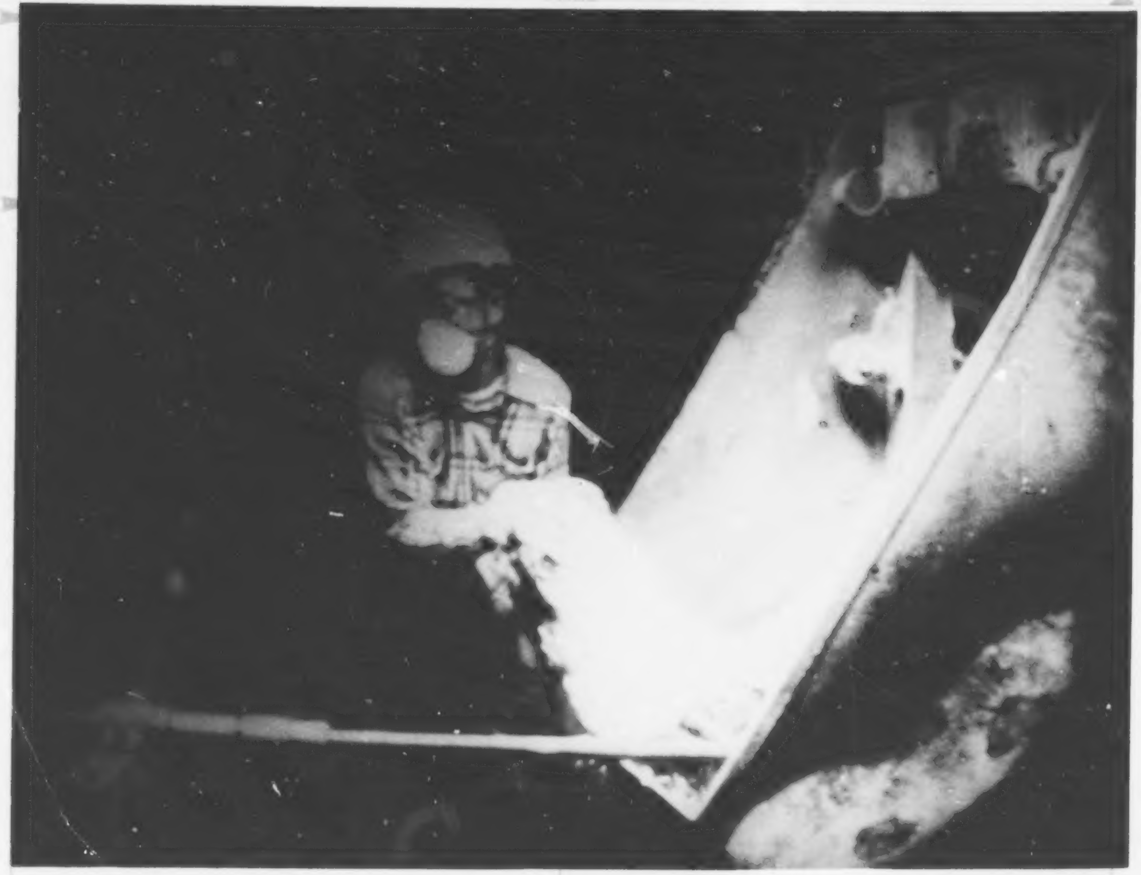

Figure 34. Manual removal of clinker from ash pit.

Slagging and Corrosion

In comparison to coal-only firing, blend firing produced more ash deposits in the following areas:

1. Back wall, near the grate and around the fly ash reinjection ports (see Figures 36 and 37).
2. Front wall, below the feeders around the tuyeres and overfire air ports (see Figures 38 and 39).
3. Right side wall, (feeder No. 6) near the grate (see Figures 40 and 41).
4. Screen tubes (very slight globules).

It was noted that the ash deposits on the side walls did not adhere to the tubes. The ash deposits attachment would occur on the refractory surface, bridge over a tube, and attach at the next refractory surface. All of the ash deposit accumulations could easily be broken and detached from the furnace walls.

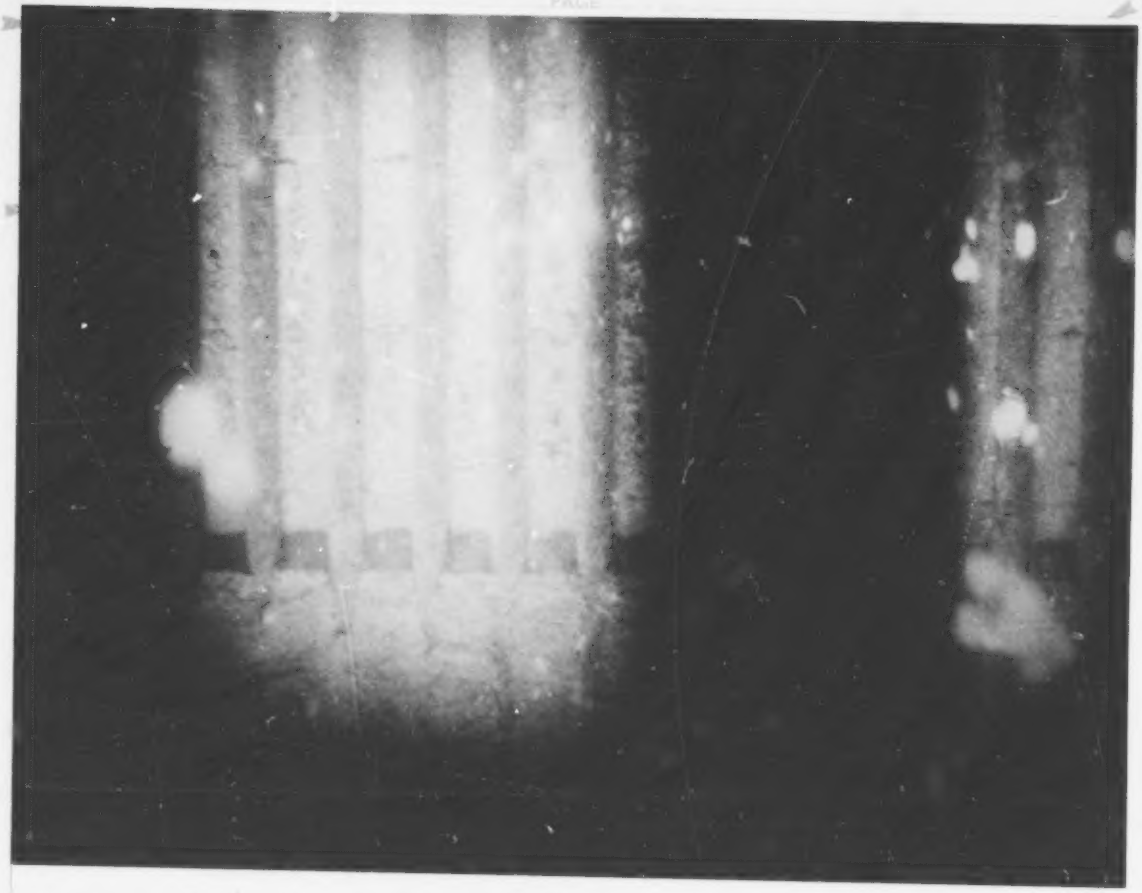

Figure 35. Flame and sparklers in screen tube region.

No difference (coal versus blend firing) could be discerned in the amount of fouling. A light fouling of the tubes occurred on the side walls from the grate surface to 15 to 20 feet above the grate.

Since corrosion potential is of paramount interest to potential users of dRDF, an analysis of the corrosion potential was performed in this demonstration test. The duration of blend burn time was too short to expect meaningful results from ultrasonic boiler tube tests or corrosion probe tests. The replacement of a boiler tube, to be later removed and studied in a laboratory, was not attempted because of the boiler outages and inspections required to carry out this procedure during the plant's high steam demand season. Therefore it was decided to perform analysis on samples of ash deposits formed during the combustion of dRDF.

Because of their previous experience in such analysis, Foster Wheeler Development Corporation was contracted to perform the ash deposit analysis. Samples of ash deposits were taken from the furnace walls and screen tubes after firing on coal only and then again after firing Teledyne dRDF and coal

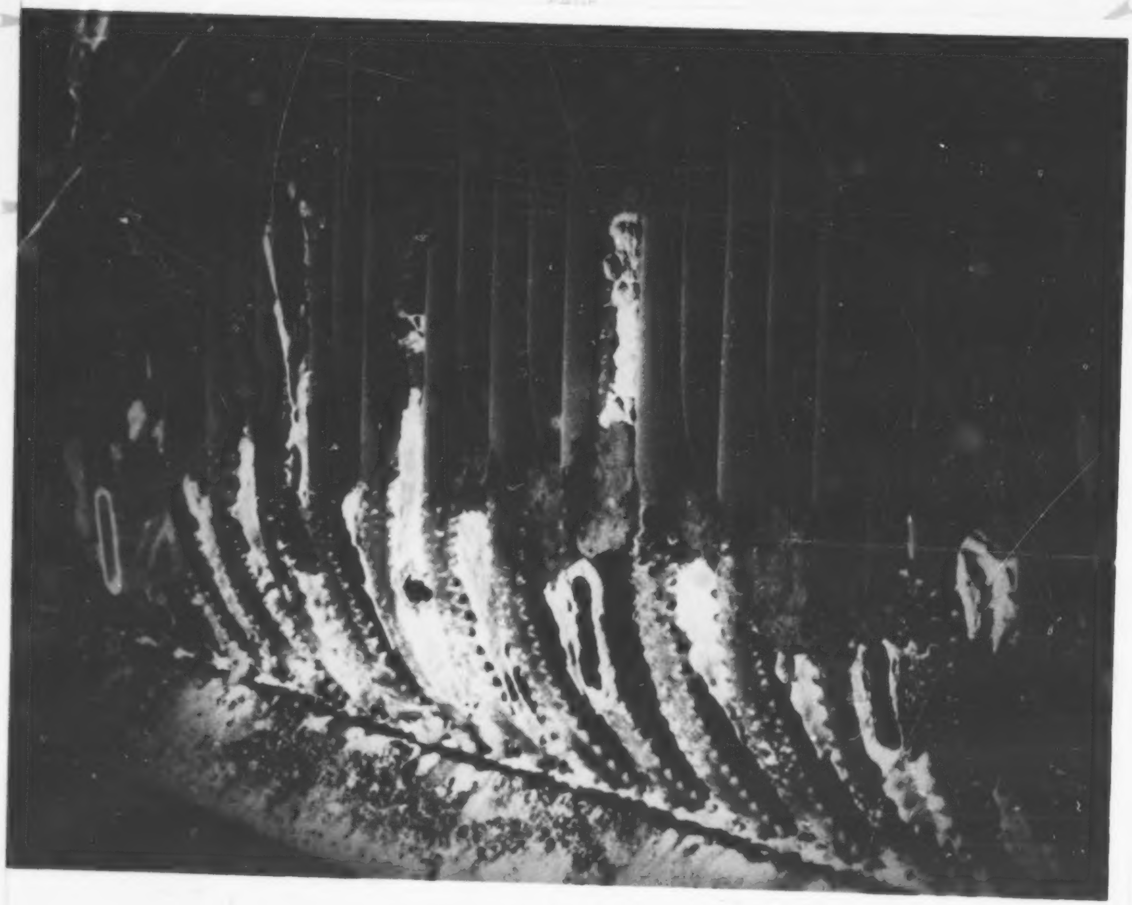

Figure 36. Rear wall after coal-only testing.

blend. The samples were analyzed by Foster Wheeler Development Corporation for ash chemistry, melting temperatures (using differential thermal analysis [DTA] and thermogravimetric analysis [TGA]), and surface morphology using the scanning electron microscope.

It was concluded that there is nothing in the chemical analysis of the dRDF blend deposits that would cause concern about corrosion problems. The thermograms indicated that there was no reaction taking place or melt formed in the deposits below 2195°F except for the ash removed from the screen tubes. An exotherm appears in the screen tube deposits at about 812° to 1120°F in the coal-only deposits and to a lesser extent in the coal/dRDF blend deposits. This exotherm is characteristic of pyrites, a common contaminant of coal. The photomicrographs from the SEM suggests that the ash deposits formed as a result of the deposit of semimolten particles in the range of 300 μm and smaller. The ash deposit from dRDF also appeared to be less dense than coal slag.

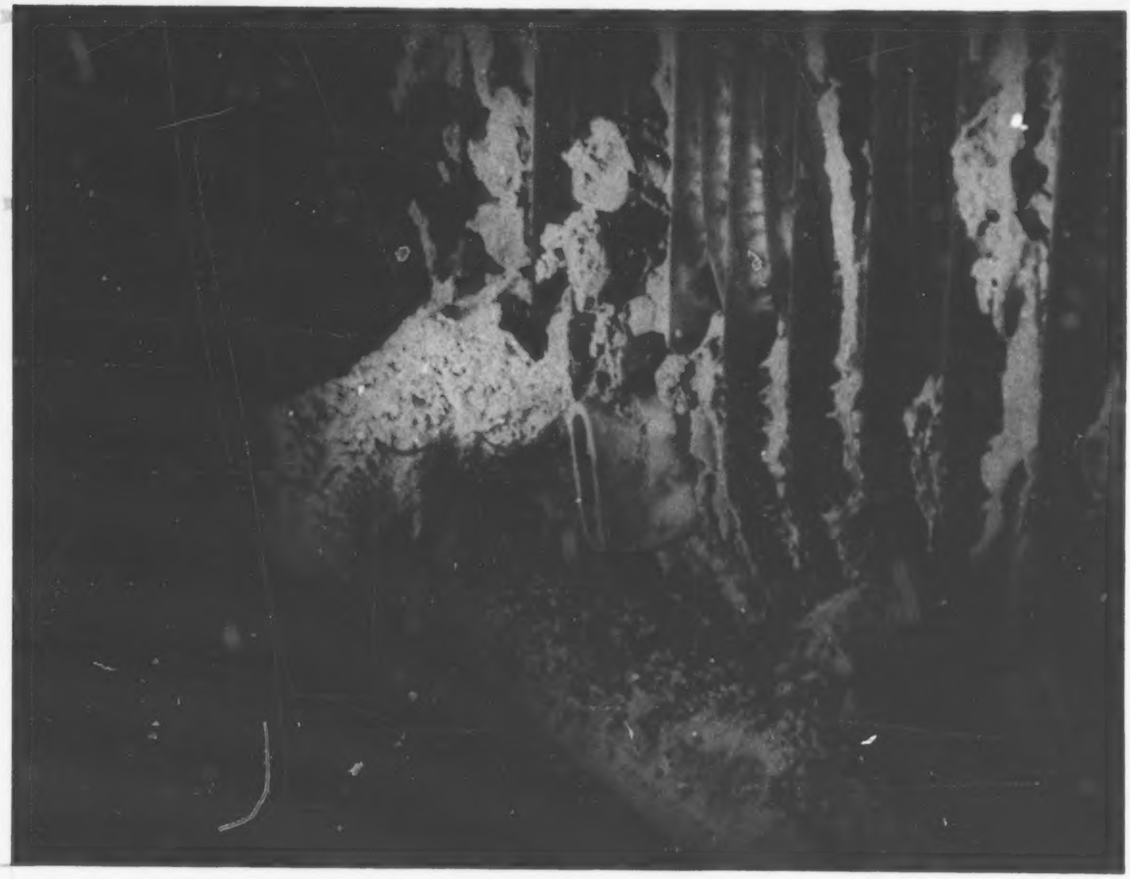

Figure 37. Rear wall after dRDF/coal blend firing.

To determine the susceptability of boiler tubes to corrosion when firing dRDF blends, metal specimens were soaked in the heated ash deposit samples at 550°, 750°, and 950°F. The weight losses of the specimens in contact with the heated ash did not deviate significantly from those specimens exposed to air at the same temperature. The complete Foster Wheeler report of the evaluation of the dRDF/coal, fuel, and ash deposits is included as Appendix D of this report.

Effects on Fly Ash

Fly ash concentration was measured in the flue gas at the inlet of the multiclone dust collector. A nonstandard sampling procedure had to be used in this aerodynamically undesirable sampling location. The results are intended to illustrate the relative changes in fly ash exposure experienced by the heat exchanger surfaces. Table 17 shows the fly ash concentrations for various load and blend conditions during the May tests. The effects of fly ash reinjection from the multiclone dust collector were compared using the quotient of the fly ash rate in pounds per hour divided by the boiler load in

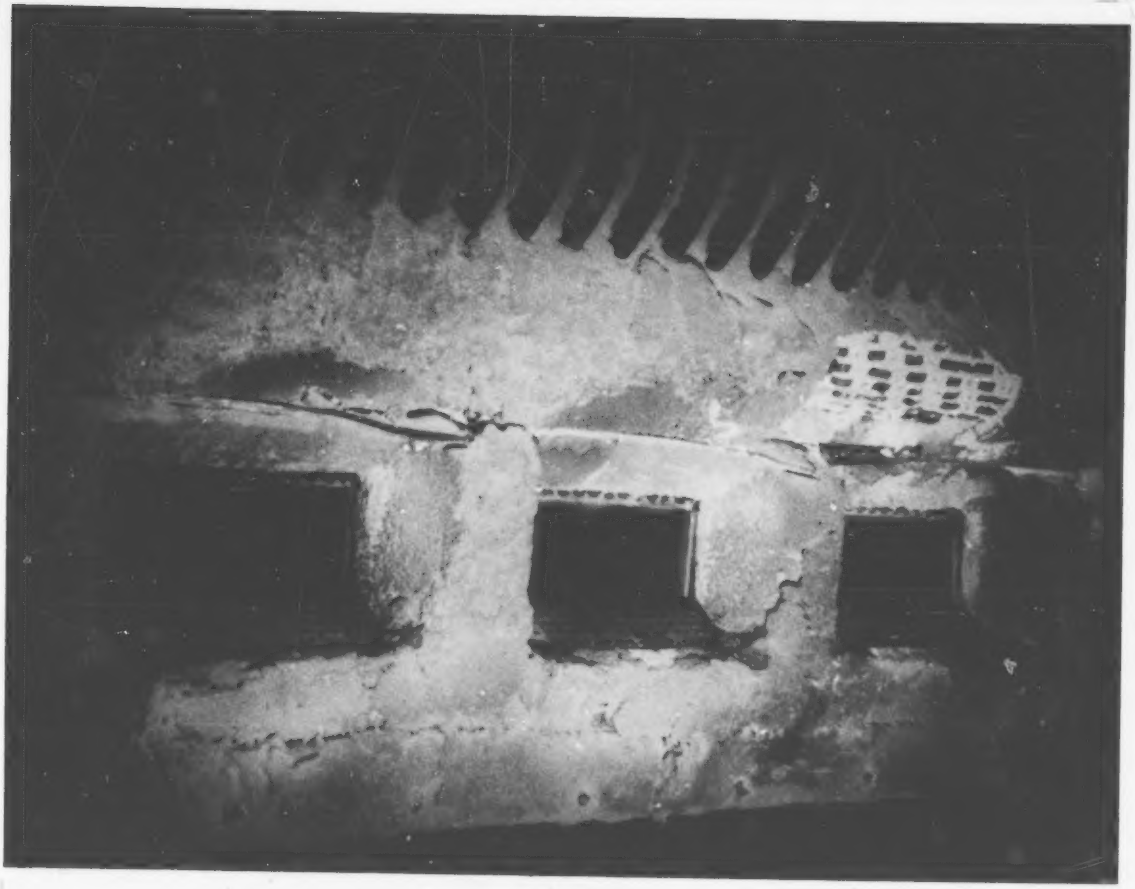

Figure 38. Front wall after coal-only firing.

percent of rated capacity. Herein this quotient is defined as the fly ash factor.

Based on this limited data at full load the dRDF blend firings showed generally higher factors than coal only. The discontinuation of fly ash reinjection dramatically reduced the fly ash factor for 1:2 (coal:dRDF) blend. But when firing coal only, this effect of fly ash reinjection was not experienced. For coal only, at lower loads, the factor increased. The fly ash effect at low load when burning dRDF blends cannot be determined from this limited data.

Surprisingly, the 1:4 (coal:dRDF) blend produced a lower factor than the 1:1 or 1:2 blends. But this reduction was probably due to the lower excess air level of the 1:4 blend firing. Excess air did not have any effect in the coal-only data, but did have a significant effect in blend firing (see Figure 42).

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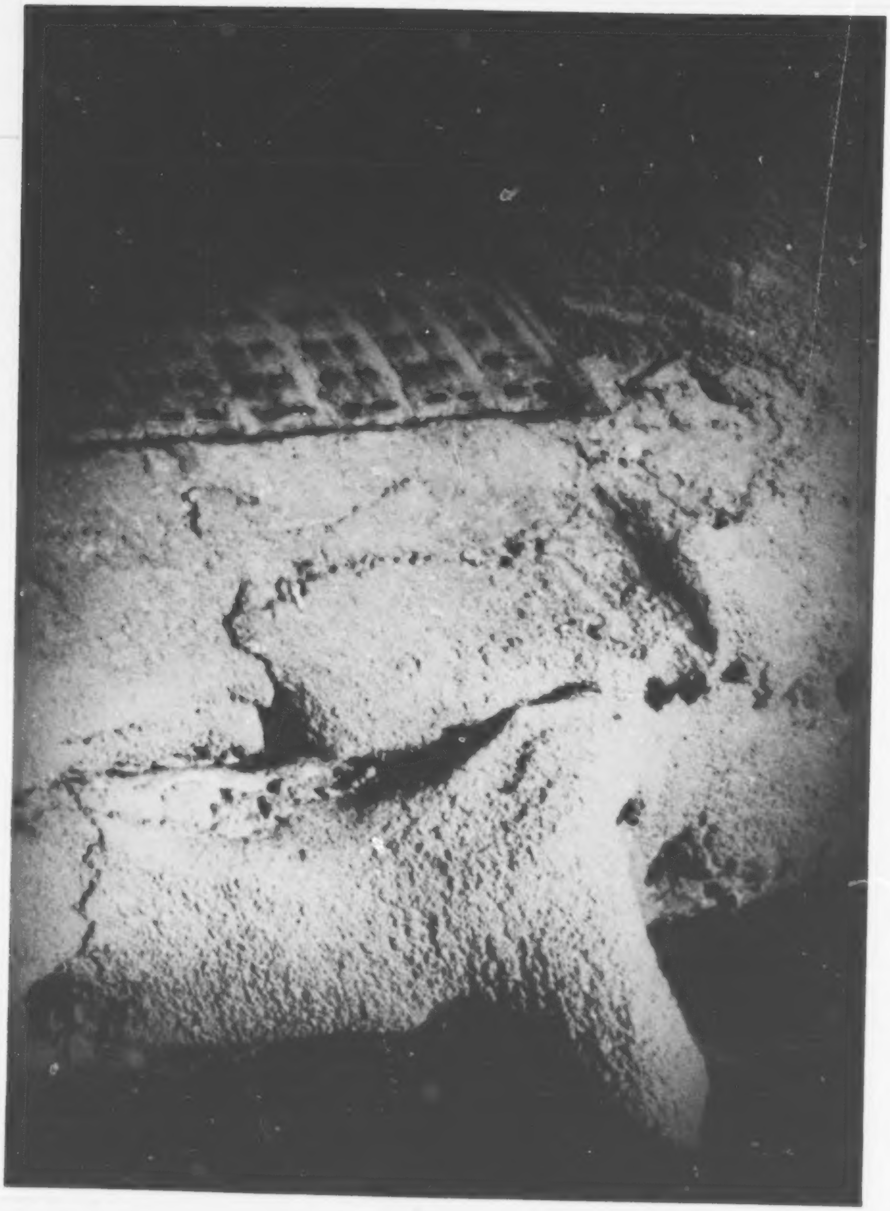

Figure 39. Front wall after dRDF/coal blend firing.

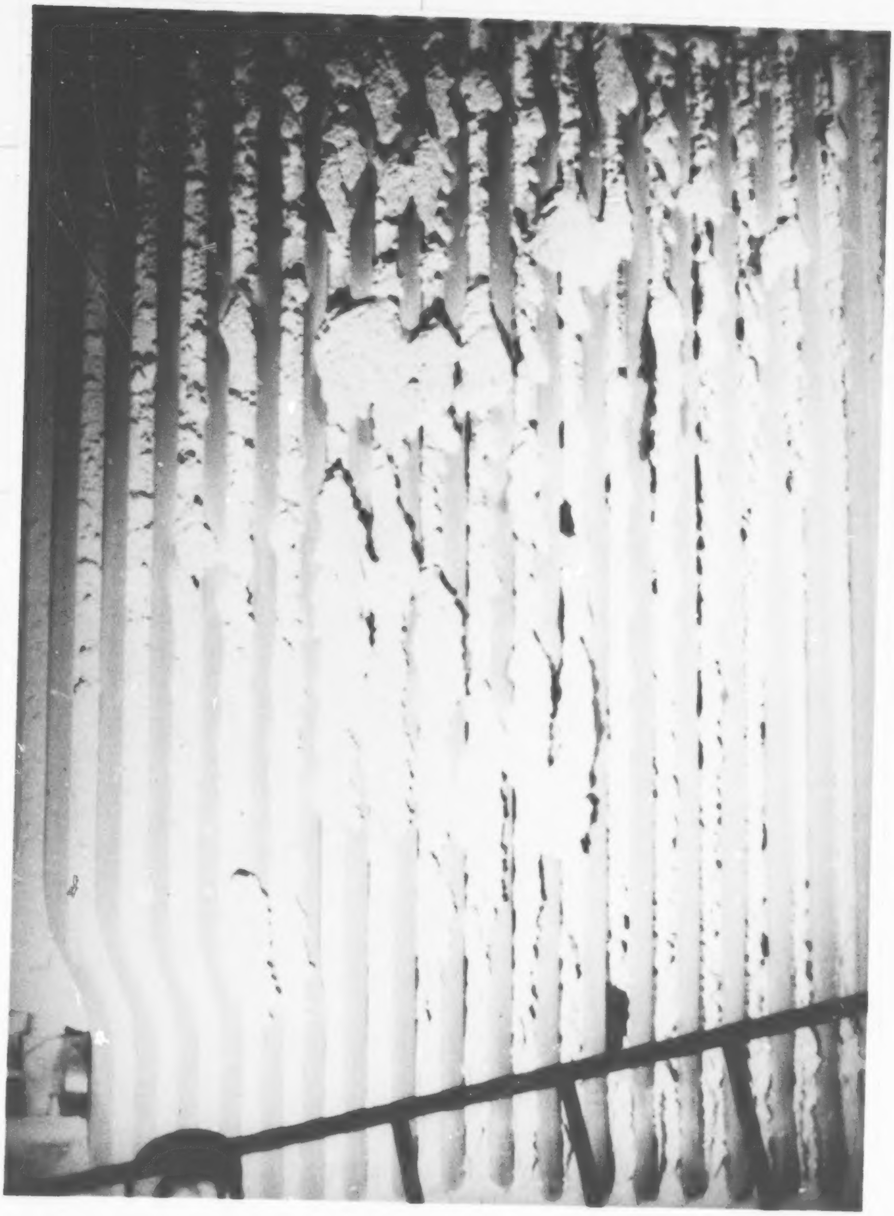

Figure 40. Right side wall after coal-only firing.

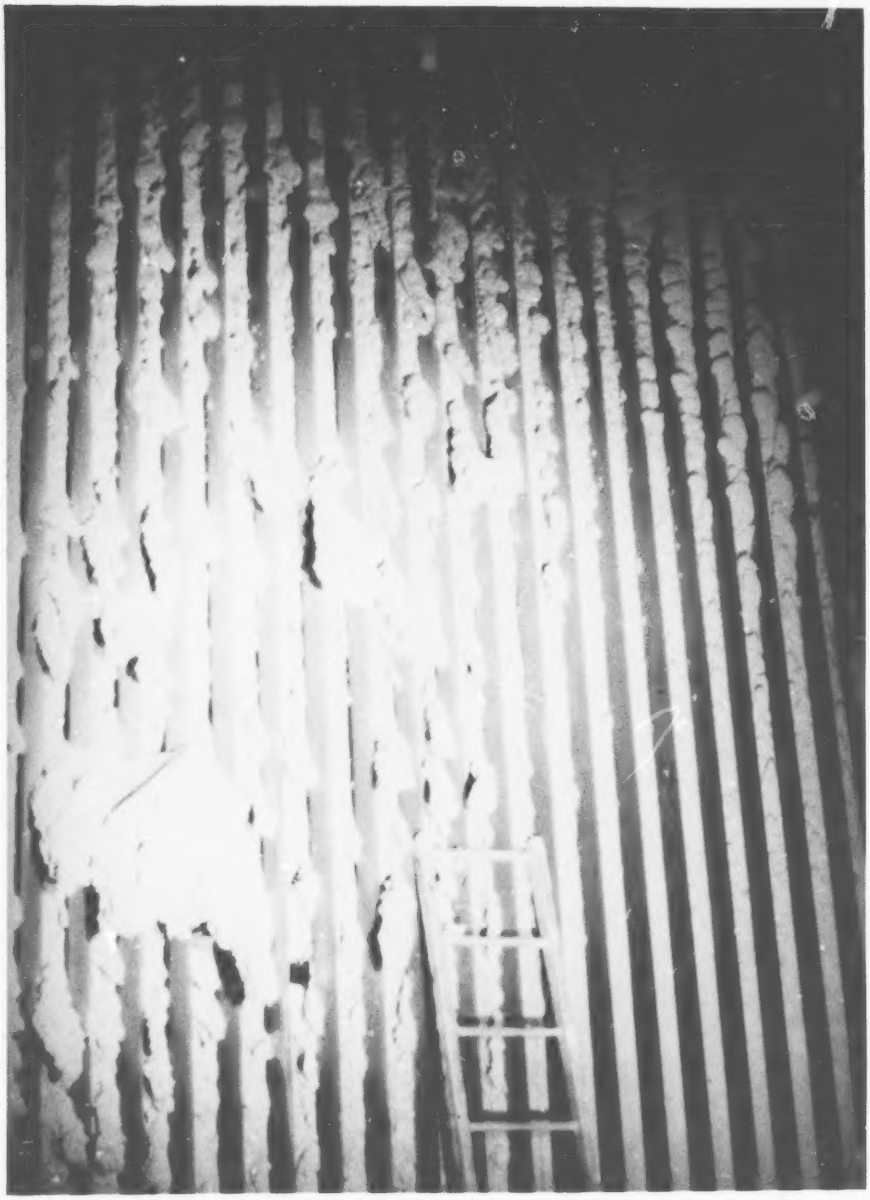

Figure 41. Right side wall after dRDF/coal blend firing.

TABLE 17. BOILER FLY ASH RELEASE

Date (mo/day)	Fuel blend (volume coal:dRDF)	Boiler load (percent MCR)	Excess air (%)	Fly ash reinjection (on/off)	Fly ash rate (lb/hr)	Fly ash factor $\frac{\text{Fly ash rate}}{\text{boiler load}}$
5/8/78	1:2	100	70	on	14,300	143
5/9/78	1:2	95	54	off	9,000	95
5/10/78	1:1	100	84	on	14,500	145
5/11/78	1:4	95	47	on	10,400	109
5/14/78	1:0	45	108	on	5,800	129
5/15/78	1:0	70	55	on	10,600	151
5/16/78	1:0	95	65	on	10,000	105
5/17/78	1:0	90	49	on	10,600	118
5/18/78	1:0	95	64	off	10,600	112

Minimum excess air and the discontinuation of fly ash reinjection reduced the fly ash factor of all dRDF blends to the same range as that measured for coal only.

Mineral Analysis

Mineral analysis of the various fuel and ash streams is shown in Table 18. As can be observed in this mineral analysis, the dRDF blends are considerably higher in sodium than coal.

MATERIAL HANDLING AND STORAGE

Pellet Storage

The pellets were stored outdoors from November 1978 through May 1979 at Erie, Pennsylvania. Attempts to keep the pellet piles covered with reinforced plastic proved to be futile. Wind ripped and shredded the plastic tarp. Therefore, the majority of the piles were exposed to the weather for 3 to 6 months. Because of this exposure these piles were capped over by a 6- to 8-in. layer of moist pellets (see Figure 43). This cap provided protection to the pellets within the pile interior. Also, the heat generated

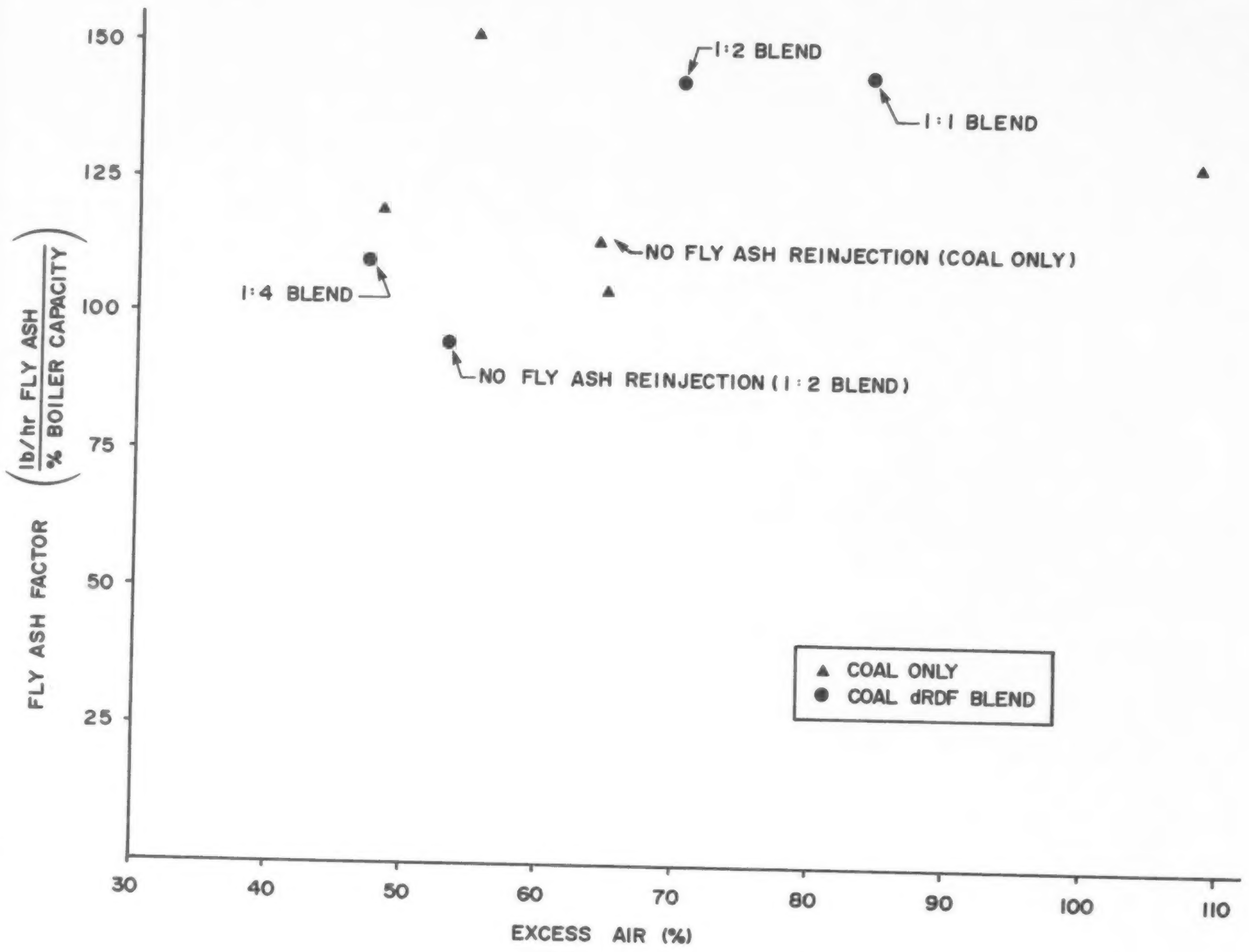

Figure 42. Excess air effect on fly ash factor.

TABLE 18. MINERAL ANALYSIS

Date	Sample type*	SiO_2 (%)	(Fe_2O_3)	AL_2O_3	T_1O_2	CaO	MgO
3/15	Blend	40.4	20.3	14.9	1.60	5.05	1.06
3/15	B-Ash	49.8	21.5	12.0	1.36	5.00	1.04
3/15	ESP-Ash	38.4	21.4	16.6	1.95	4.23	1.05
3/15	Mult.	43.8	20.9	15.8	1.26	5.27	1.13
5/8	Blend	47.7	9.5	18.1	2.25	5.56	1.37
5/8	B-Ash	44.4	10.4	17.1	1.76	10.1	3.76
5/8	ESP-Ash	42.6	14.2	21.1	1.59	3.56	0.84
5/8	Mult.	43.0	19.4	24.1	0.87	2.70	0.78
5/8	B.O.Ash	47.3	14.5	18.0	1.06	5.20	1.85
5/16	Coal	41.4	17.9	24.4	1.38	3.32	1.47
5/16	B-Ash	34.3	11.5	14.2	1.23	17.4	9.89
5/16	ESP-Ash	43.9	14.8	24.7	1.17	3.07	0.75
5/16	Mult.	46.2	16.7	19.5	1.78	4.73	1.28
5/16	B.O.Ash	44.2	15.1	22.7	0.88	4.21	1.85

(continued)

TABLE 18. (continued)

Date	Sample type	P_2O_5	SO_3	Na_2O	K_2O	CaO + MgO	$\frac{CaO + MgO}{Fe_2O_3}$
3/15	Blend	0.62	6.90	2.58	0.95	6.11	0.30
3/15	B-Ash	0.09	2.78	2.74	0.88	6.04	0.31
3/15	ESP-Ash	0.95	6.05	2.90	1.06	5.28	0.25
3/15	Mult.	0.73	1.38	3.00	0.99	6.40	0.31
5/8	Blend	0.03	5.30	2.66	0.95	6.93	0.73
5/8	B-Ash	0.40	2.28	1.80	0.96	13.86	1.33
5/8	ESP-Ash	1.19	4.70	2.65	1.07	4.40	0.31
5/8	Mult.	0.32	0.60	0.96	0.98	3.48	0.81
5/8	B.O.Ash	0.47	1.88	1.93	0.99	7.05	0.49
5/16	Coal	0.46	2.13	0.78	0.95	4.79	0.27
5/16	B-Ash	0.15	5.33	0.80	0.90	27.29	2.37
5/16	ESP-Ash	0.58	1.83	0.91	0.90	3.82	0.26
5/16	Mult.	0.68	0.93	2.59	1.01	6.01	0.36
5/16	B.O.Ash	0.42	1.60	0.89	0.96	6.06	0.40

* Blend = coal/dRDF fuel blend
B-Ash = bottom ash
ESP Ash = fly ash collected by ESP
Mult. = fly ash collected by multiclone
B.O. Ash = fly ash sampled at boiler outlet

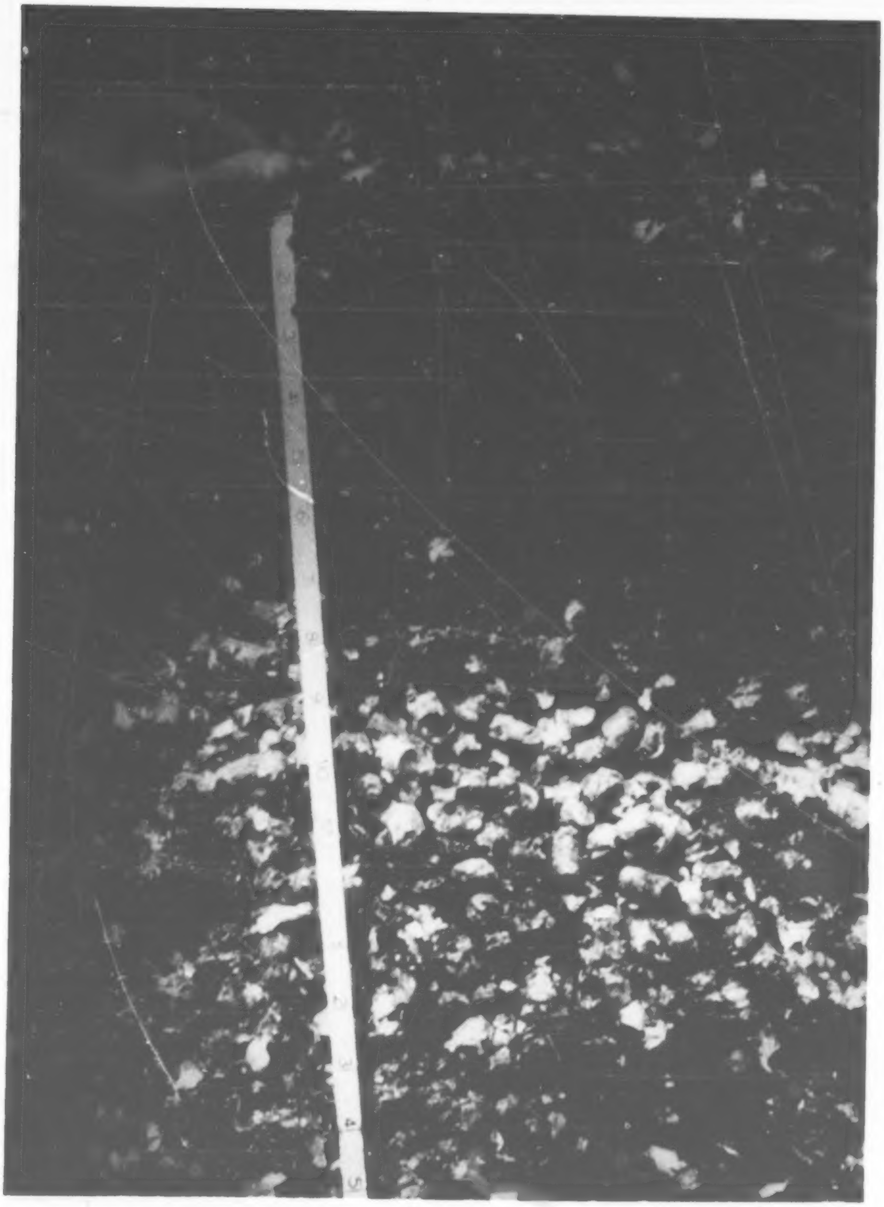

Figure 43. Crust on top of weathered dRDF pile.

within the piles (approximately 140°F) helped to evaporate moisture from the pile interior.

The outdoor storage of the dRDF during the winter resulted in an increase in moisture and fines content of the pellets. Table 19 shows the changes in fuel properties. The storage caused the density of Teledyne and NCRR pellets to change very little.

TABLE 19. dRDF AS-SHIPPED AND AS-BURNED PROPERTIES

	NCRR			Teledyne		
	As-shipped average	As-burned Min.	As-burned Max.	As-shipped average	As-burned Min.	As-burned Max.
Moisture (percent)	17	18.0	29.5	16	14.0	33.7
Bulk density (lb/ft^3)	38	31	35	35	29	37
Fines (percent weight)	12	39	54	*	10	48

* Not measured

While deterioration of the dRDF caused no combustion problems, a slight increase in wet flue gas heat losses occurred. The condition of these pellets did cause considerable fuel handling problems. The serrated edges of the swollen pellets (see Figure 44) and the fibrous shape of the fines (see Figure 45) caused the dRDF to resist flowing, both when alone and when blended with coal.

Blending and Conveying

Truck loads of pellets were dumped through a grizzly grate into two hoppers where they were fed onto conveyors via reciprocating feeders. This operation generally proceeded well except for pellet hang-up in the shallow sloped hoppers. As the level of pellets above the feeders decreased, the feed rate correspondingly decreased. Additional labor was required to rod the pellets into the feeders (see Figure 46).

Since the pellets are lower in bulk density than coal, the conveyor system can carry a larger volume of pellets than of coal. But this larger volume resulted in increased conveyor spillage (see Figure 47). Some housekeeping was required to clean up spilled pellets in the conveyor galleyways. Due to the high moisture content of the pellets, dusting was a minor problem. As a precaution face mask respirators were worn by personnel

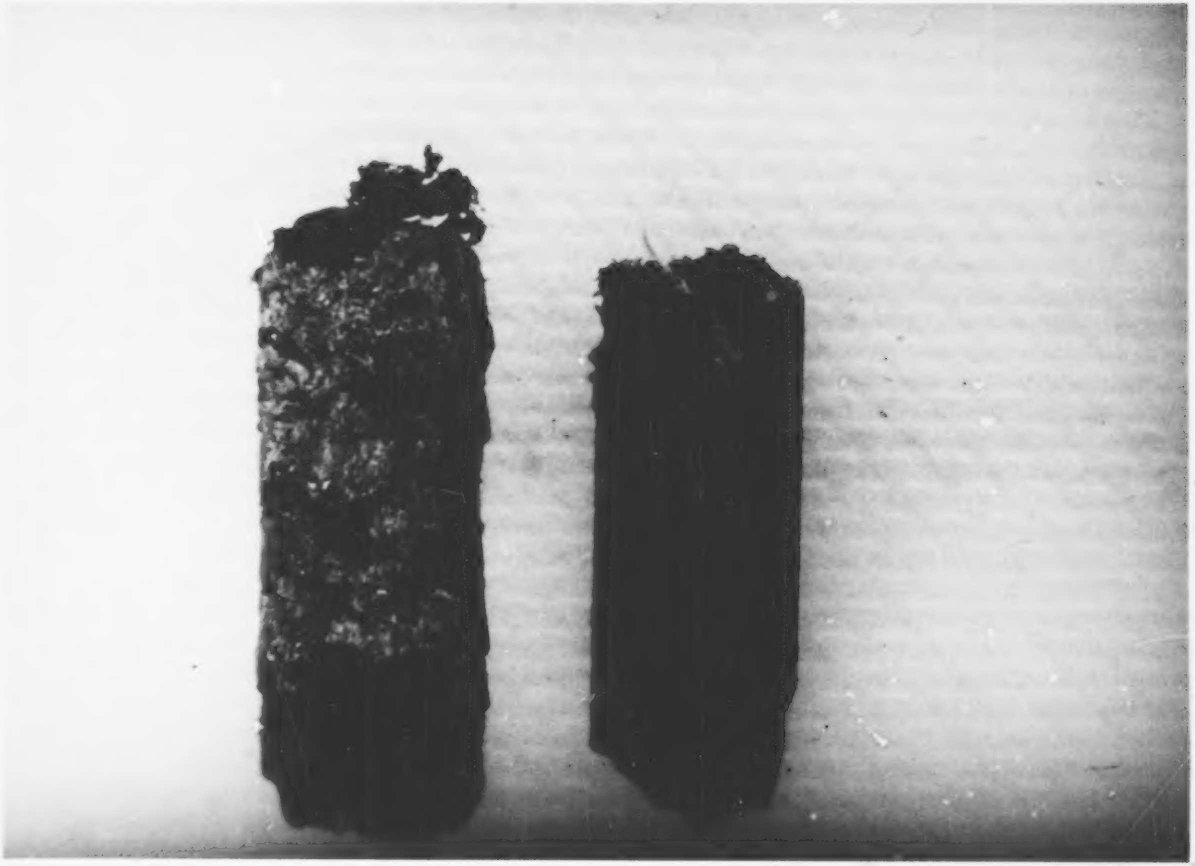

Figure 44. Storage effects on pellets (weathered pellet on left; fresh pellet on right).

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Figure 45. Weathered pellets with high fines content.

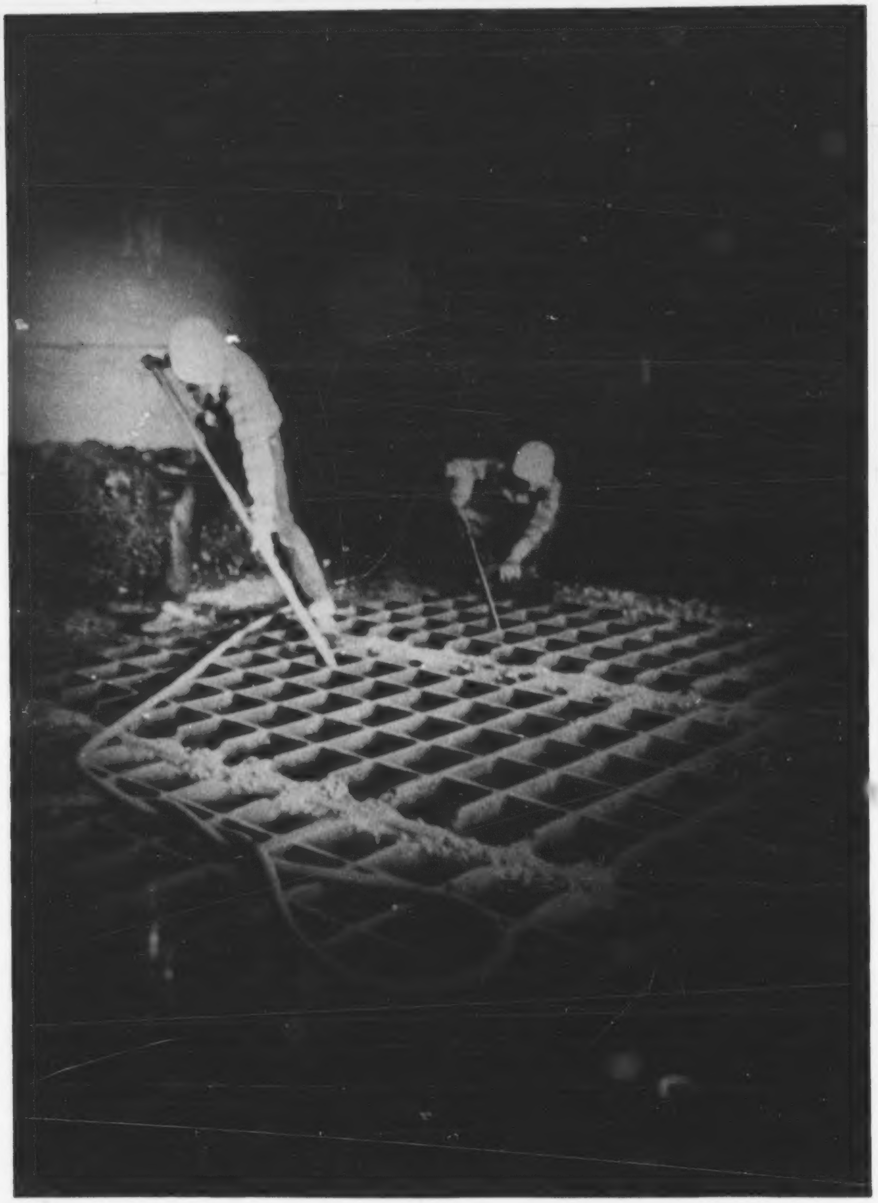

Figure 46. Rodding dRDF in feed hopper.

Figure 47. dRDF spillage from conveyor.

in the bunker area. The pellets conveyed well with homogeneous mixing occurring as the coal and pellets transferred from one conveyor to another.

Bunker and Distribution Chutes

When firing with coal only, the use of rappers to release coal hung up on the side walls of the bunker generally proved to be effective (see Figure 48). When firing blends, both air lance rodders and rappers were required to keep the fuel from hanging up in the bunker. Air blasters mounted on the sides of the bunkers were only effective when the bunker was at a low level. When the bunker was full, the low bulk density and elasticity of the pellets effectively absorbed the air blast shock wave.

On a few occasions, bridging occurred inside the distribution chute. Due to the large amount of fines in the pellets (50 percent by weight less than 3/8 in.) severe "rat-holing" of the coal:dRDF fuel occurred in the

Figure 48. Air blasters and rappers mounted on bunkers.

bunkers. Continual rodding (air lance) had to be employed to move the fuel blend out of the bunker. Angles of repose greater than 90° were experienced (see Figure 49).

Feeding

The pellets and coal were well mixed when they reached the feeders. Periodic examination of the feeders revealed a buildup of wet slack coal and dRDF fines on the front of the pusher plate. The distribution of the fuel blend on the grate revealed that four times as much (by weight) of the fuel was being deposited 5 feet in from the feeder than 5 feet from the back wall. The spreader speed is linked to the pushplate speed which was increased to compensate for the lower heat density of the fuel blend. When operating at rated capacity, fuel impinged on the rear wall because of the speed-up of the spreaders. However, during both blend and coal-only tests, the spreaders were operated within the recommended speed range of 630 to 795 rpm. At full load, the grate speed was increased from 8 to 9 ft/hr to 10 to 13 ft/hr when shifting from coal-only to 1:2 blend.

Figure 49. dRDF blend hung up in bunker.

EMISSIONS RESULTS

Particulate and gaseous emissions from the steam generator were evaluated while burning coal/dRDF blends and coal only. Identical tests were conducted throughout the program to permit evaluation of the impact that dRDF had on the normal emissions from this steam generator.

In Appendix B, Data Columns 1 through 60 include all of the measured emissions data. Equations 1 through 60 in Appendix C illustrate the derivation of those results reported in Appendix B. Each line of data is a set of results representing the conditions for one Method 5 period (2 1/2 hours of testing). The operational data of the steam generator and emissions data for other pollutants were also averaged over this same time period. On a normal test day, two Method 5 tests were conducted, yielding two sets of emissions results.

Particulate Emissions

Mass rate of particulate emissions was measured for every test at the electrostatic precipitator inlet. This location was selected because the particulate characteristics of any uncontrolled boiler would probably be similar to those measured at this location in the system.

Results of the particulate emissions measured at the precipitator inlet are shown in Figure 50. These results are expressed in pounds of particulate per million Btu heat input. As Figure 50 indicates, there is no statistically discernible difference between the emissions of coal only and the emissions of coal/dRDF blend. The data is very scattered because these tests were conducted under actual plant operating conditions. Excess air is believed to have a major effect on particulate emissions. The wide range of excess air levels was the same for both coal only and for blend firing (see Figure 31).

To evaluate the effect of dRDF on precipitator performance, Method 5 tests were conducted at the precipitator outlet whenever the boiler was operated at its rated capacity.

Table 20 shows the particulate emissions measured at the ESP outlet. At full boiler load the NCRR pellets and coal blend at a 1:2 ratio averaged the same mass loading at the precipitator outlet as found in the coal baseline tests performed that same month. The Teledyne pellets at a 1:2 blend also averaged the same outlet mass loading as the coal baseline tests in May.

In the coal/dRDF boiler tests that were conducted at the Maryland Correctional Institute in Hagerstown, Maryland, it was found that the emitted particulate size decreased as the amount of dRDF in the fuel blend increased. This finding was supported by the March coal baseline and NCRR blend tests where the NCRR pellets blended at a 1:2 ratio (1 volume coal:2 volumes dRDF) exhibited a smaller emitted particulate size than coal only (see Figure 51).

However, testing of the Teledyne blends in May did not support these results entirely (see Figure 52). During these tests the particulate size decreased as the percentage of dRDF was increased. The coal only particulate had about the same size distribution as the 1:4 coal/dRDF blend. The March coal only and the May coal only tests emitted about the same sized particulates, while the largest sized particulates of the test series were emitted by the Teledyne pellet and coal mixtures.

The NCRR pellets were manufactured in the same way as those used in the Maryland Correctional Institution tests. Therefore it is not surprising that the fuel blends with NCRR pellets emitted small particulate as they did in the Maryland test.

The larger particulate sizes emitted from the Teledyne pellets/coal blends are probably attributable to the low ash content and well formed pellet shape of the Teledyne dRDF.

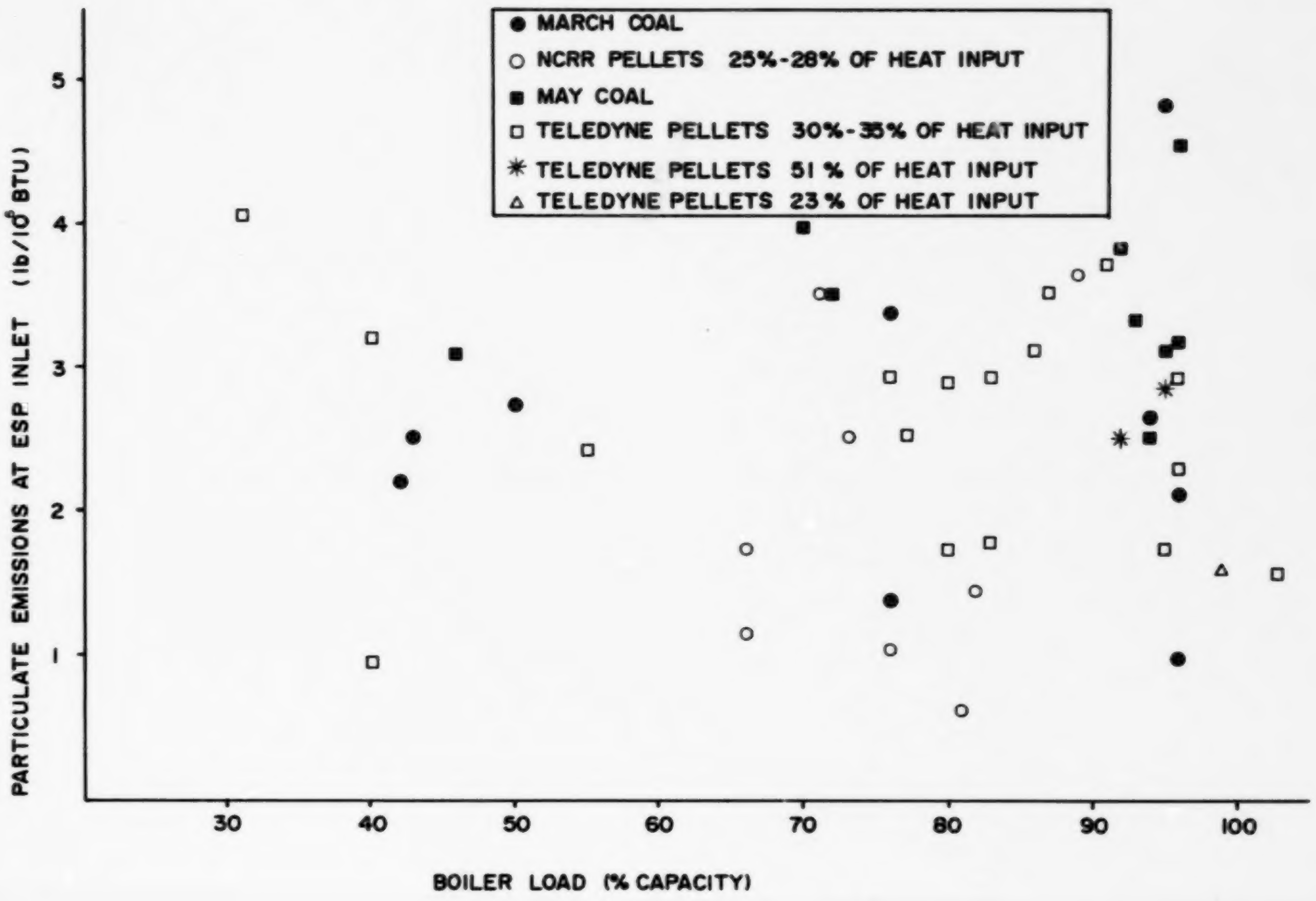

Figure 50. ESP inlet particulate emissions.

TABLE 20. PARTICULATE EMISSIONS ESP OUTLET

Fuel	Number of tests	Emission ($lb/10^6$ Btu)
March coal baseline	4	.51
NCRR pellets at 24 to 28 percent by heat substitution	3	.52
Teledyne pellets at 30 to 35 percent by heat substitution	13	.16
May coal baseline	6	.15

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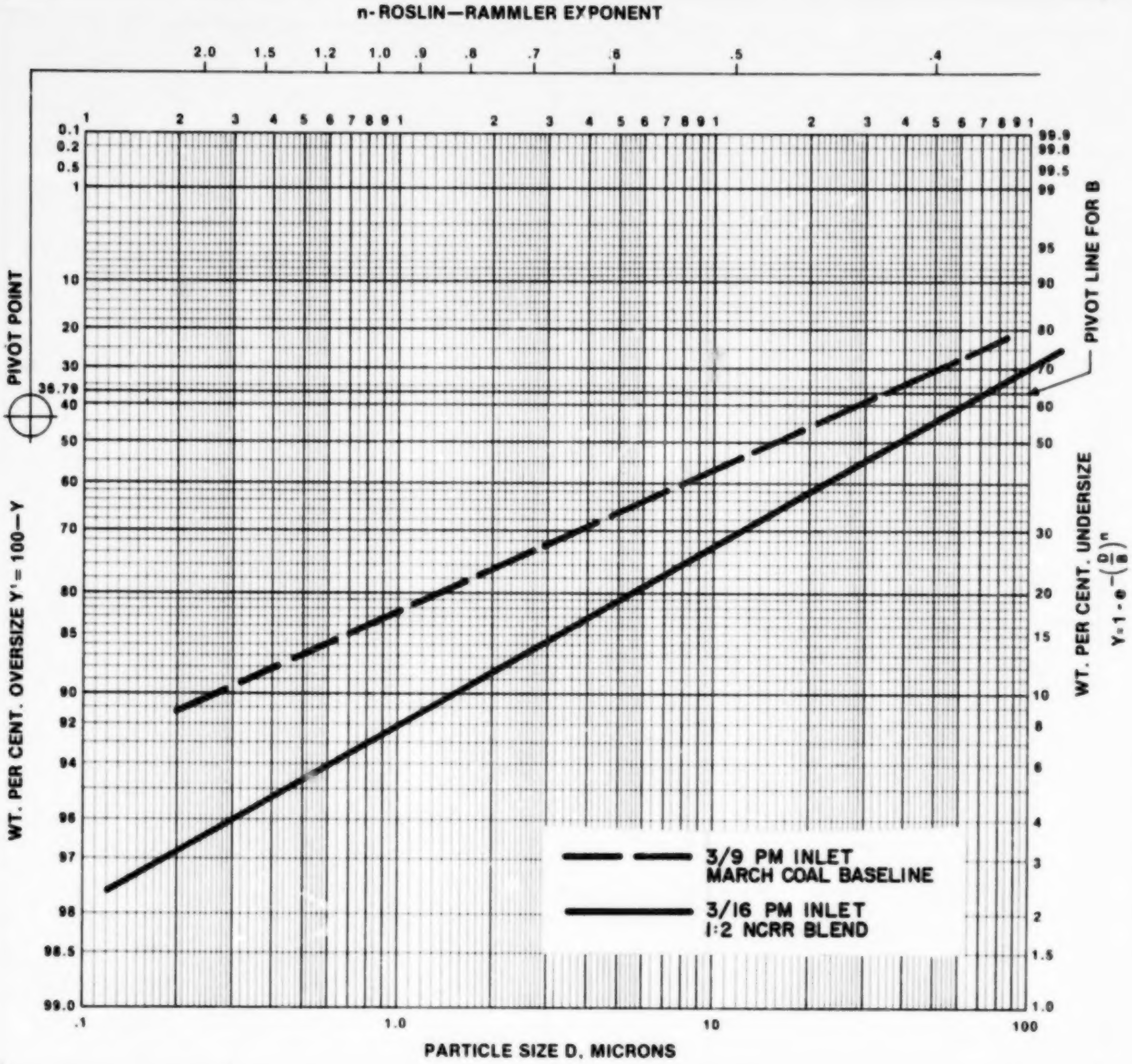

Figure 51. March test, ESP inlet particulate size distribution.

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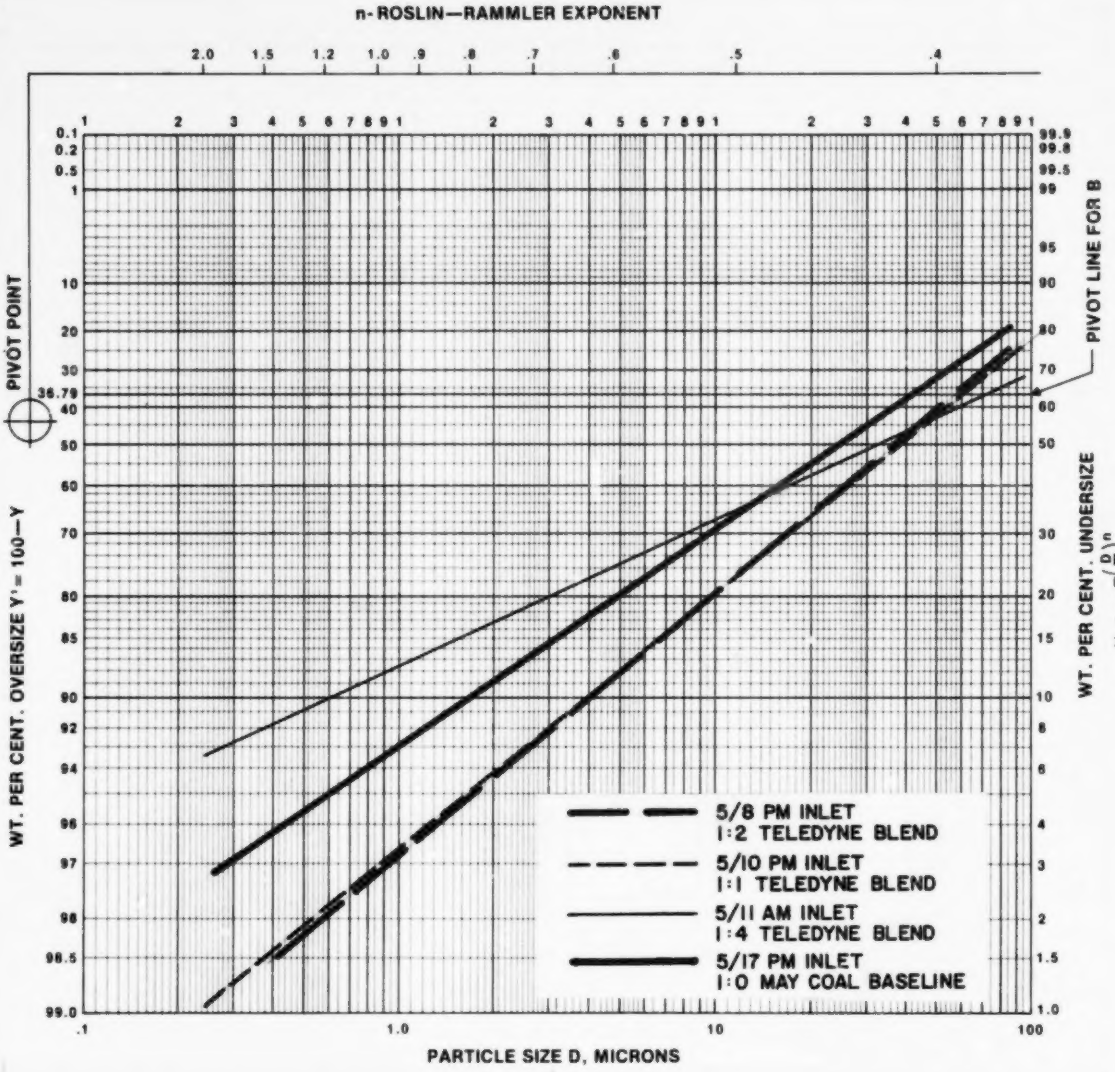

Figure 52. May test, ESP inlet particulate size distribution.

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No significant change was found in particulate size at the ESP inlet due to fly ash reinjection from the multiclones. Figure 53 shows the effect that fly ash reinjection had on size distribution when firing a 1:2 blend of coal and Teledyne dRDF as tested in April where a small amount of change occurred. Figure 54 shows a replication of this test in May and no change in size occurred. However, when firing coal only, an increase in particulate size consistently occurred when fly ash reinjection was discontinued. Figure 55 illustrates this shift. The reason for this shift is that under normal fly ash reinjection conditions, the carbonaceous particulate from coal firing is reinjected until the combustion process reduces its size below the cut diameter of the multiclones. Both coal-only and blend firing demonstrated the same shift in unburnt combustibles in the multiclone and ESP fly ash, when multiclone reinjection was terminated. The combustible particulate from blend firing is apparently smaller in size and thus escapes the collection devices.

At the ESP outlet, the NCRR fuel blend showed a reduction in particle size (compared to that of firing coal only) similar to the reduction observed at the ESP inlet (see Figure 56).

However the Teledyne fuel also showed no change in the particulate size when comparing 1:2 blend to coal-only firing as it did in its ESP inlet tests (see Figure 57).

Fly ash reinjection from the multiclones had little effect on the size of emitted particulate from the ESP outlet. Little difference could be discerned both with or without dRDF substitution as can be observed in Figures 58, 59, and 60.

Attempts were made to measure in situ resistivity of the fly ash upstream of the ESP. Frequent malfunctions of and erratic data from the Wahlco Resistivity Probe caused rejection of the in situ data. Subsequently, samples of the ESP capture fly ash were subjected to laboratory resistivity analysis. Results of this analysis are shown in Table 21. These results indicate that resistivity increased when firing dRDF. However, the resistivities for the fly ash of coal alone were abnormally low due to the high percentage of unburnt carbon in that fly ash. For efficient fly ash precipitation, resistivities should be in the range of 10^8 to 10^{10} ohm-cm. Although the data indicates that resistivity increased when the fly ash reinjection was discontinued during dRDF firing, this increase cannot be considered significant because the measurements are near the minimum detection level of the laboratory test method.

In the coal:dRDF blend firing tests at the Maryland Correctional Institution, resistivity increased above the 10^7 ohm-cm coal baseline to an average 10^{12} ohm-cm for 1:2 blend by volume. Since the addition of dRDF usually resulted in a reduction of unburnt carbon in the fly ash, dRDF addition generally causes an increase in fly ash resistivity. Therefore, blends of dRDF could be expected to improve precipitator performance if the fly ash resistivities for coal are low (below 10^6 ohm-cm). However, if the resistivities are acceptable when burning only coal, dRDF addition could reduce precipitator performance by increasing resistivity to above the acceptable range.

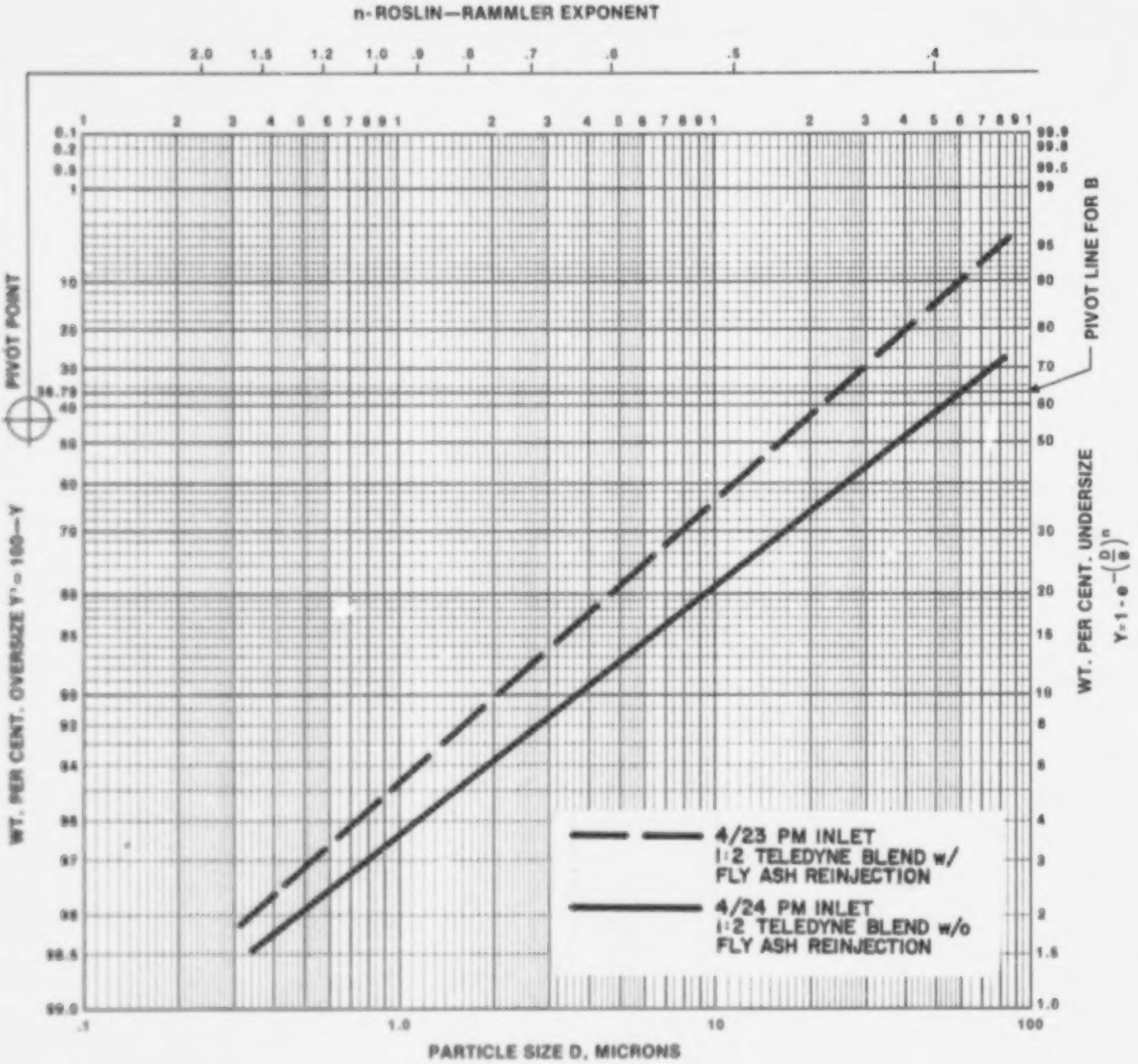

Figure 53. Fly ash reinjection effect on ESP inlet particulate size distribution.

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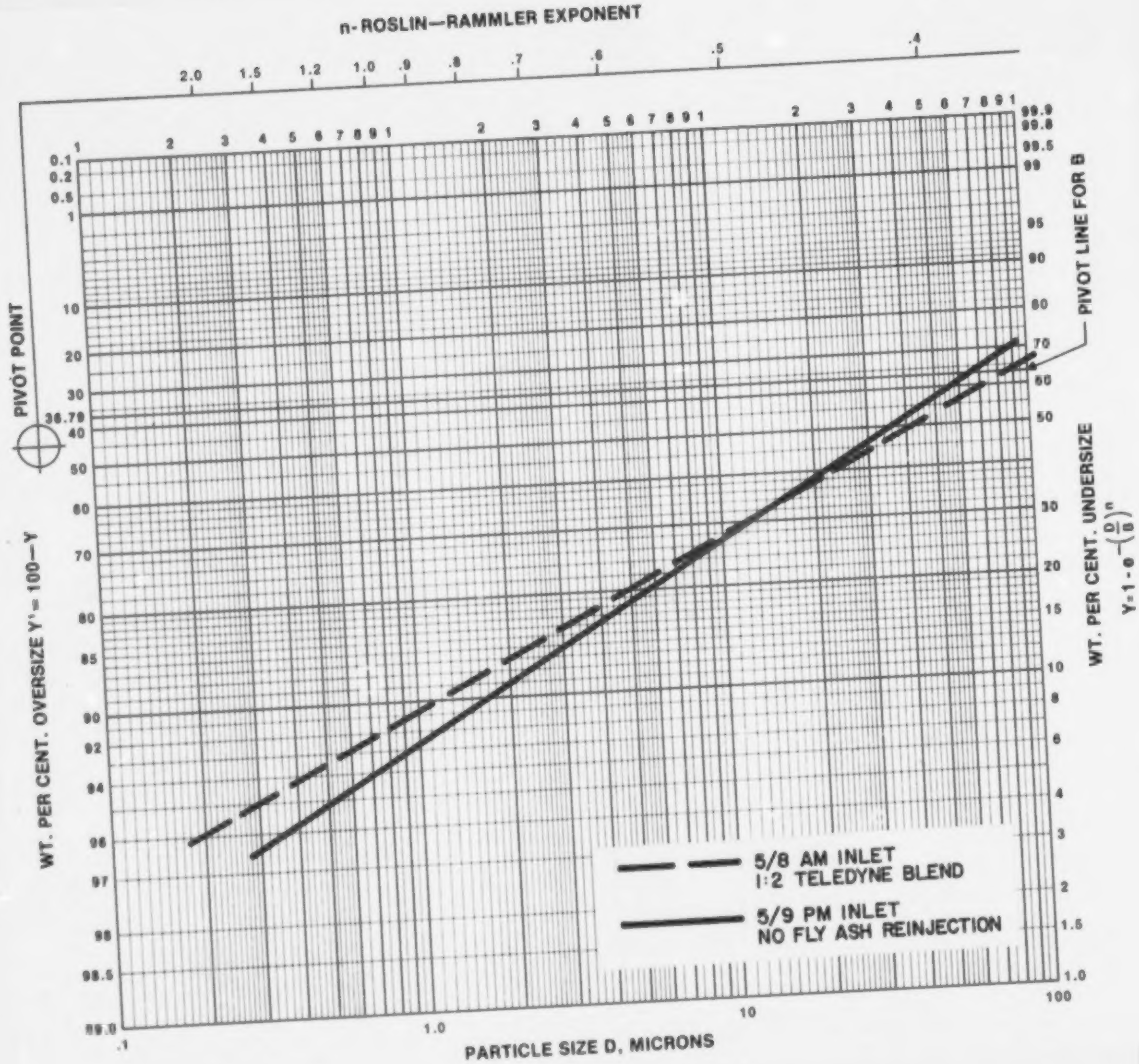

Figure 54. May blend, fly ash reinjection effect on ESP inlet particulate size distribution.

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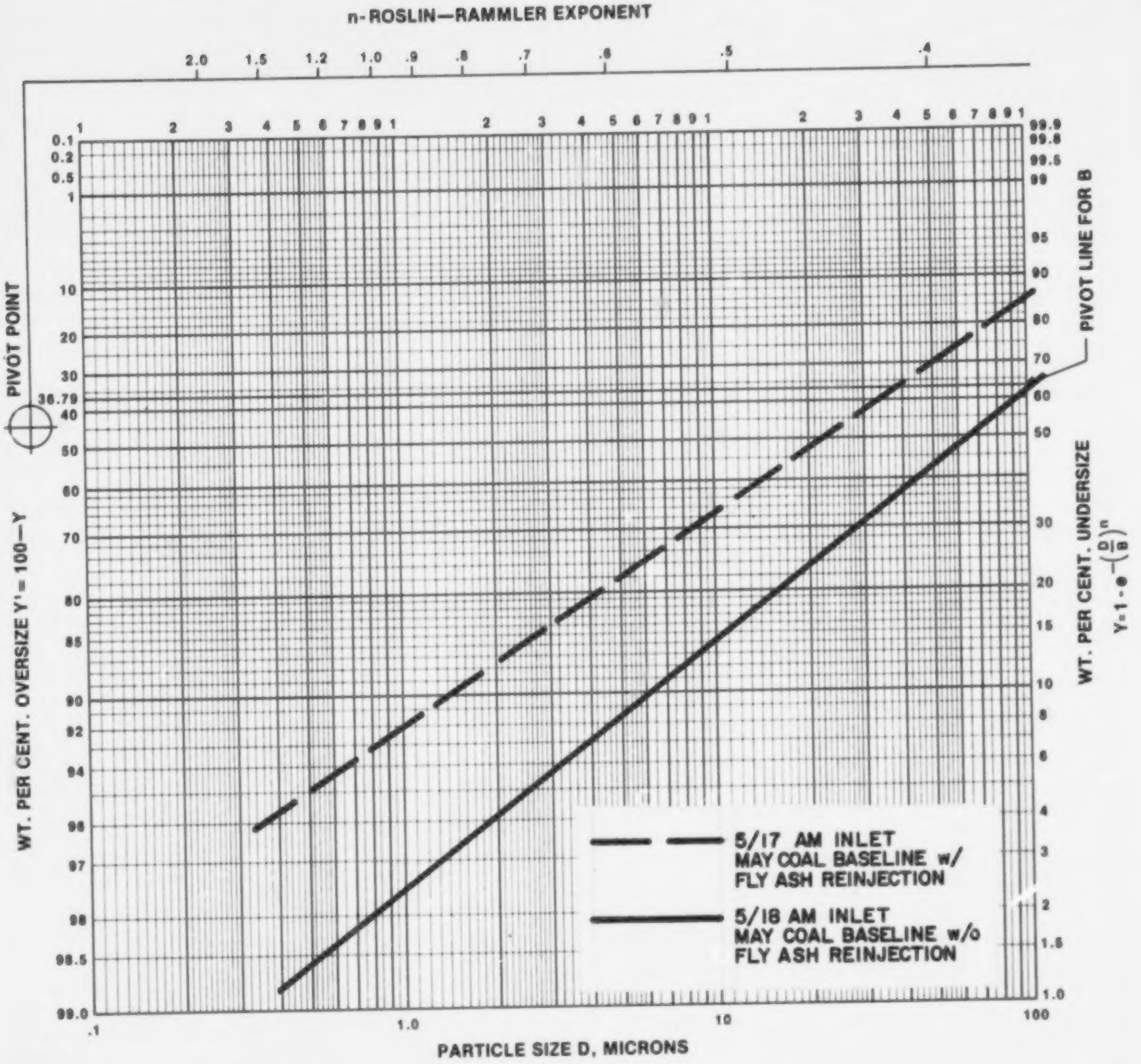

Figure 55. May coal, fly ash reinjection effect on ESP inlet particulate size distribution.

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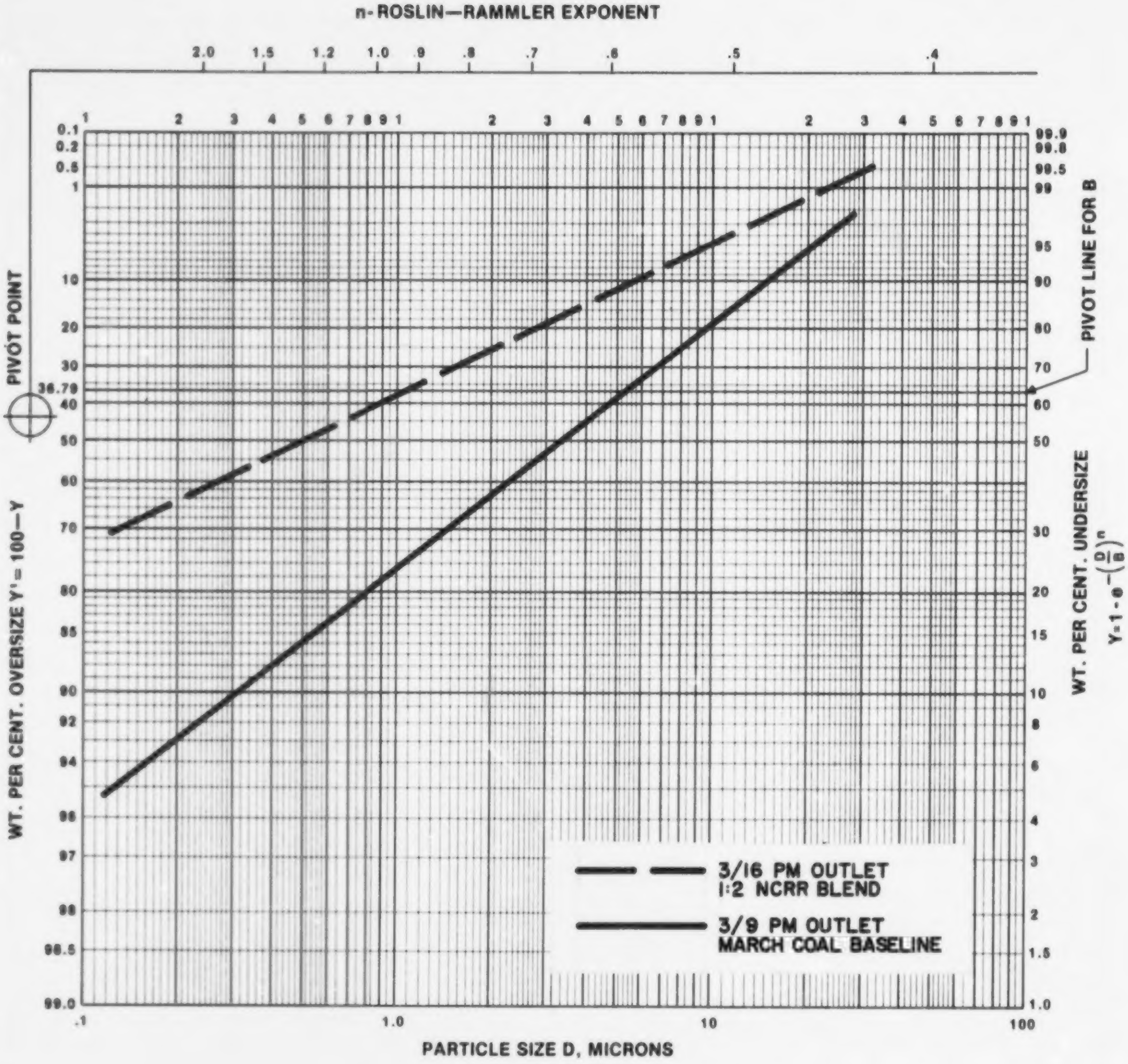

Figure 56. March, ESP outlet particulate size distribution.

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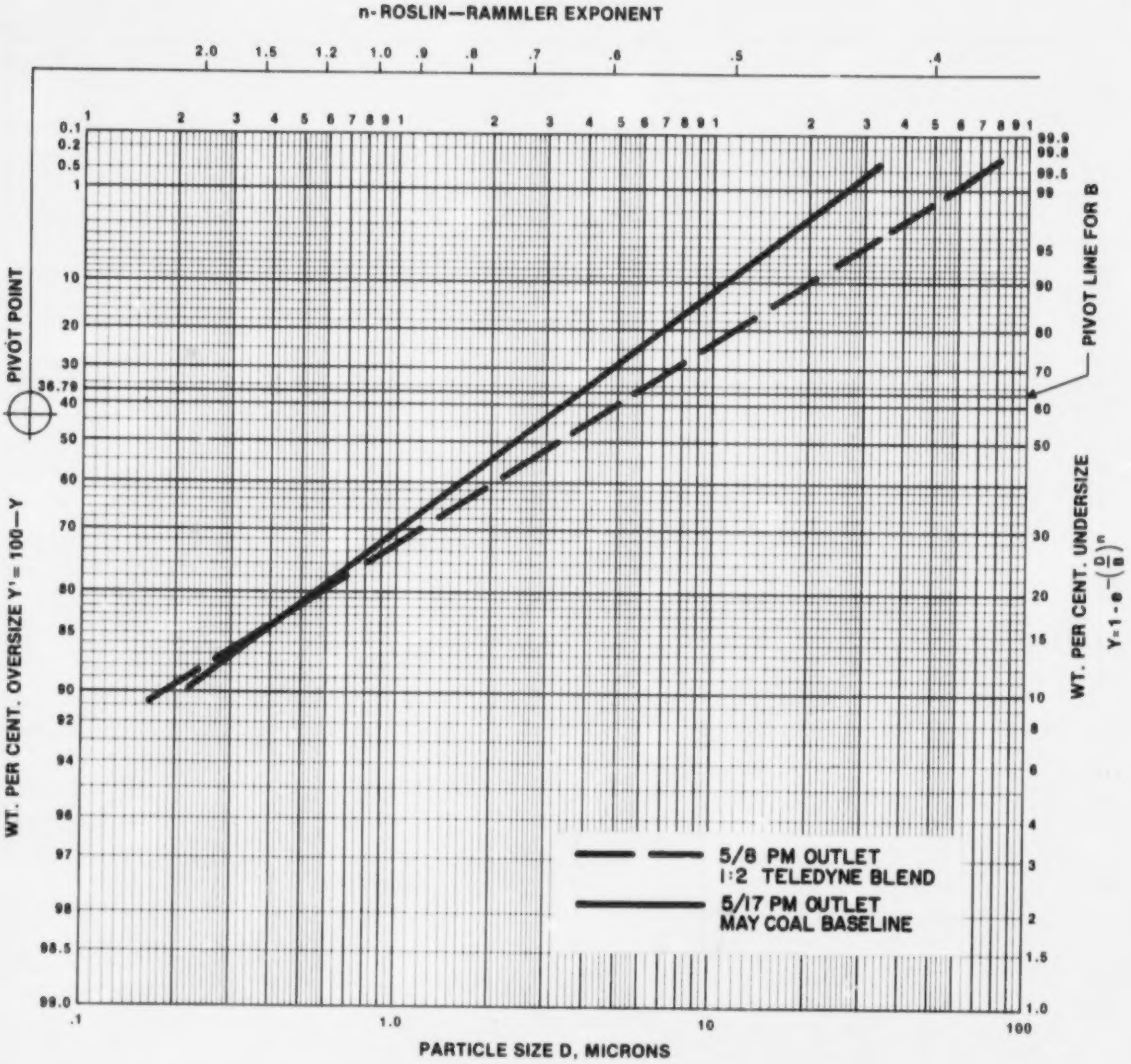

Figure 57. May, ESP outlet particulate size distribution.

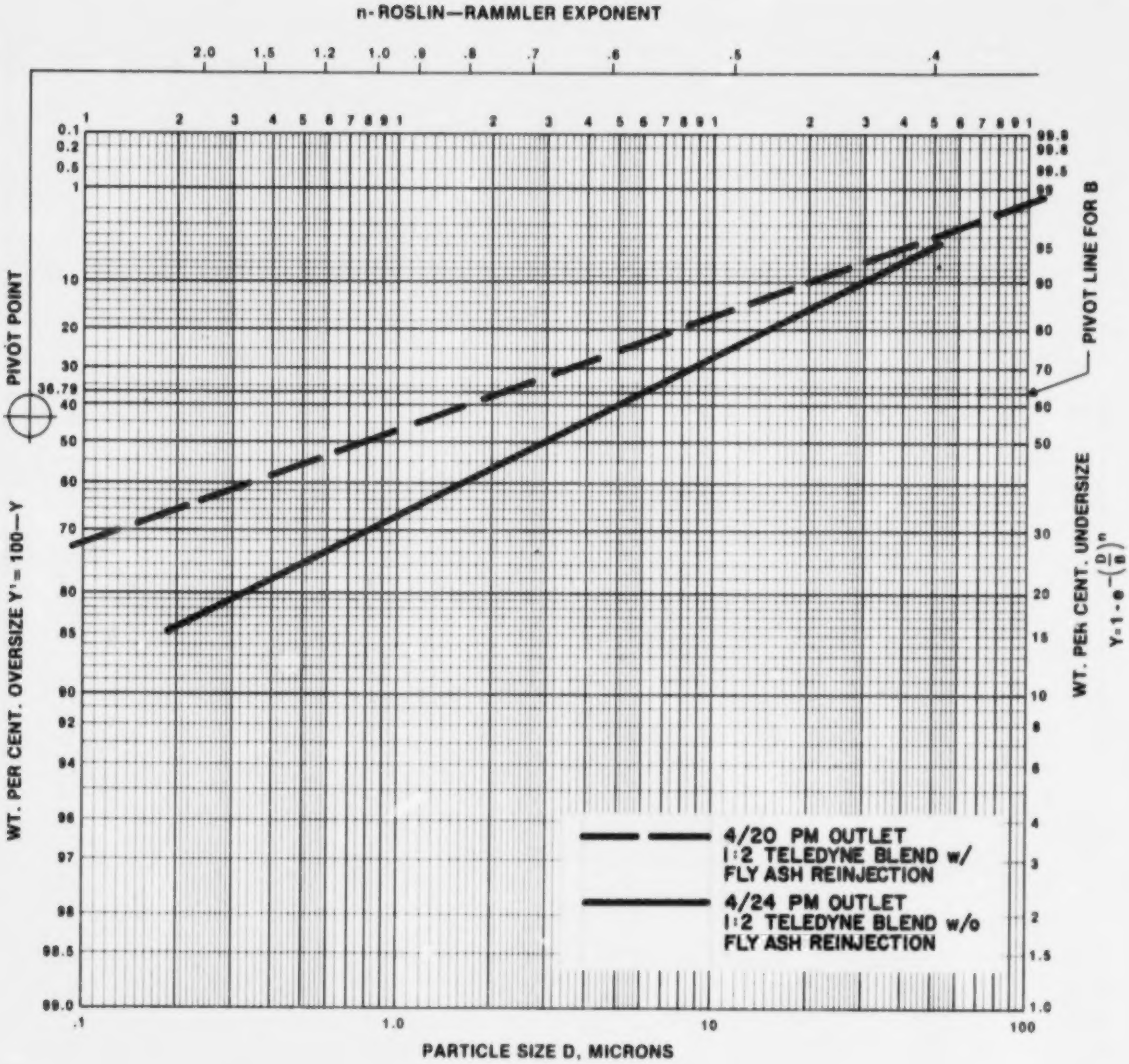

Figure 58. March blend, fly ash reinjection effect on ESP outlet particulate size distribution.

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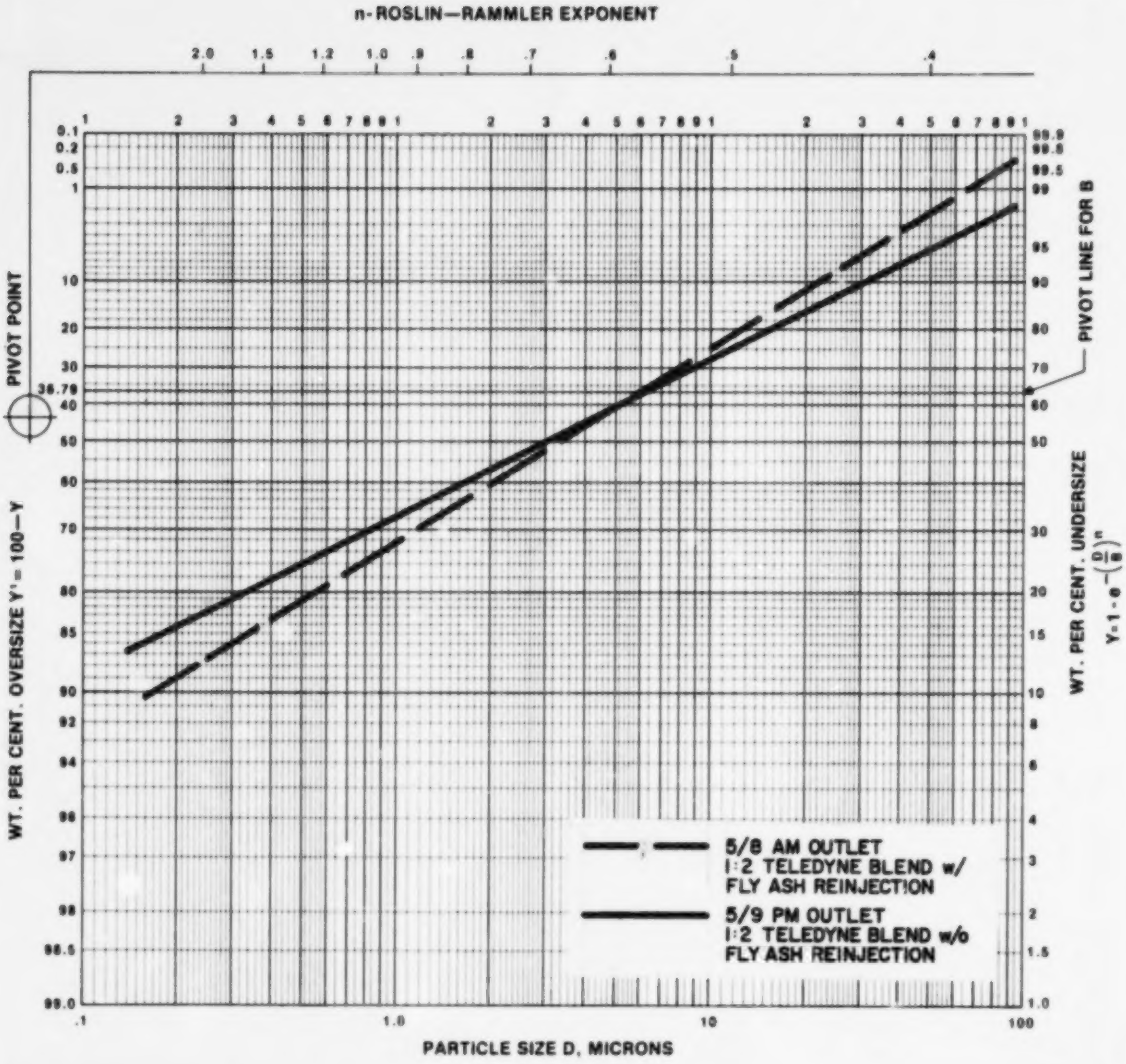

Figure 59. May blend, fly ash reinjection effect on ESP outlet particulate size distribution.

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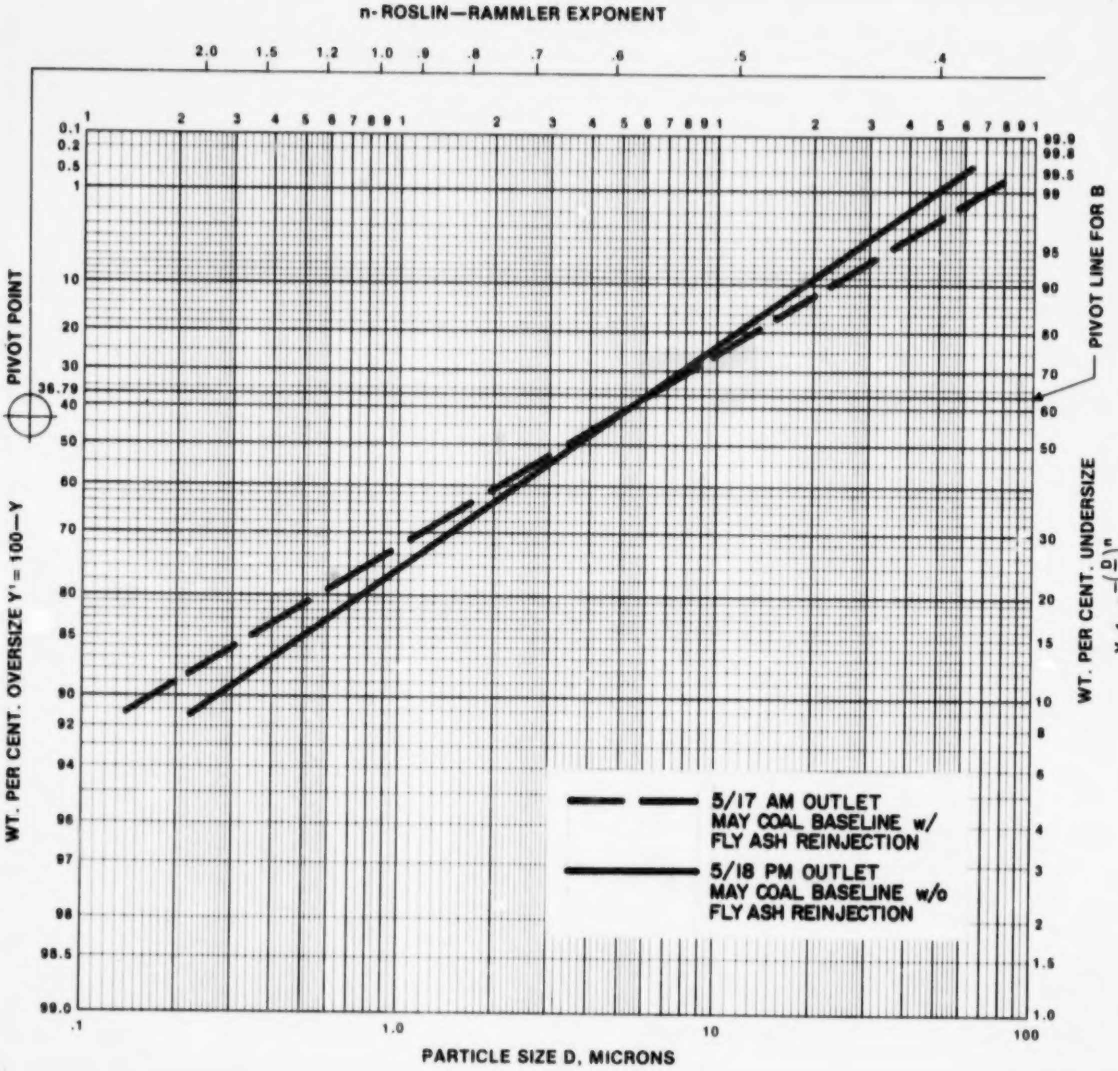

Figure 60. May coal, fly ash reinjection effect on ESP outlet particulate size distribution.

TABLE 21. FLY ASH RESISTIVITY--BOILER OPERATED AT MAXIMUM CAPACITY

Date	Volumetric blend (coal:dRDF)	Resistivity (ohm-cm)	Unburnt combustibles (percent)	Comment
May 8	1:2 Teledyne	1.56×10^6*	25.6	
May 9	1:2 Teledyne	1.05×10^8	20.7	No reinjection
May 16	1:0	2.09×10^4*	39.7	
May 18	1:0	4.36×10^4*	33.6	No reinjection

* Below 10^7 (the minimum applicable range for ASME Power Test Code 28 which was used in this analysis).

Atomic absorption analysis was used to determine the concentrations of five metals in the particulate sampled from the ESP inlet. Extensive metals analyses were performed in the Maryland Correctional Institution tests but only five were found to be significant. These metals are lead, zinc, cadmium, chromium, and beryllium. Table 22 shows the metals content of the particulate collected at ESP inlet by the EPA Method 5 tests. Table 23 shows the actual emission of each metal as measured at the the ESP inlet. Inlet concentrations were measured because only the inlet samples were of sufficient quantity and condition for atomic absorption analysis. Results from the Maryland Correctional Institution tests indicated that these metals tend to show higher concentrations on smaller particulates. Particulate control devices are most efficient at collection of large particulates. This implies that at the outlet of a particulate control device (where a greater percentage of smaller particulates exists), the metals emissions would not be reduced in proportion to the particulate emissions rate reduction.

Precipitator performance was monitored at full boiler load only. Particulate concentrations were measured at both the inlet and outlet of the ESP. Electrical operating conditions of the ESP were also monitored.

Figure 61 shows the precipitator collection efficiency as a function of dRDF substitution in the fuel. As this Figure indicates, the distribution of collection efficiencies for dRDF blends is the same as the distribution for coal only. Such efficiency distribution occurred because other variables have more impact on collection efficiency than coal:dRDF blend ratio.

TABLE 22. METALS CONCENTRATION OF ESP INLET PARTICULATE

Dates	dRDF heat sub. (percent dRDF)	Pb (mg/g)	Zn (mg/g)	Cd (mg/g)	Cr (mg/g)	Be (mg/g)
3/7	0	.215	.445	.005	4.13	.009
3/7	0	1.120	2.180	.027	1.21	.006
3/13	28	1.670	2.23	.030	6.14	.011
3/13	28	1.710	2.40	.022	1.54	.008
3/14	28	1.420	2.23	.026	9.17	.009
3/14	24	1.43	2.13	.018	2.37	.011
3/15	26	1.17	1.66	.015	2.55	.005
5/15	0	0.258	1.49	.007	1.34	.010
5/15	0	0.331	1.88	.006	1.25	.009

TABLE 23. METALS EMISSIONS TO ESP INLET

Dates	dRDF heat sub. (percent dRDF)	Pb	Zn	Cd	Cr	Be
				(gr/10^6 Btu)		
3/7	0	2.23	4.61	.052	42.8	.093
3/7	0	27.0	52.5	.650	29.1	.144
3/13	28	20.9	27.9	.376	76.9	.138
3/13	28	30.0	42.2	.386	27.1	.140
3/14	28	11.8	18.6	.216	76.4	.075
3/14	24	35.1	52.3	.442	58.2	.270
3/15	26	30.2	42.9	.387	65.9	.155
5/15	0	6.41	37.0	.174	33.3	.248
5/15	0	9.27	52.6	.168	35.0	.252

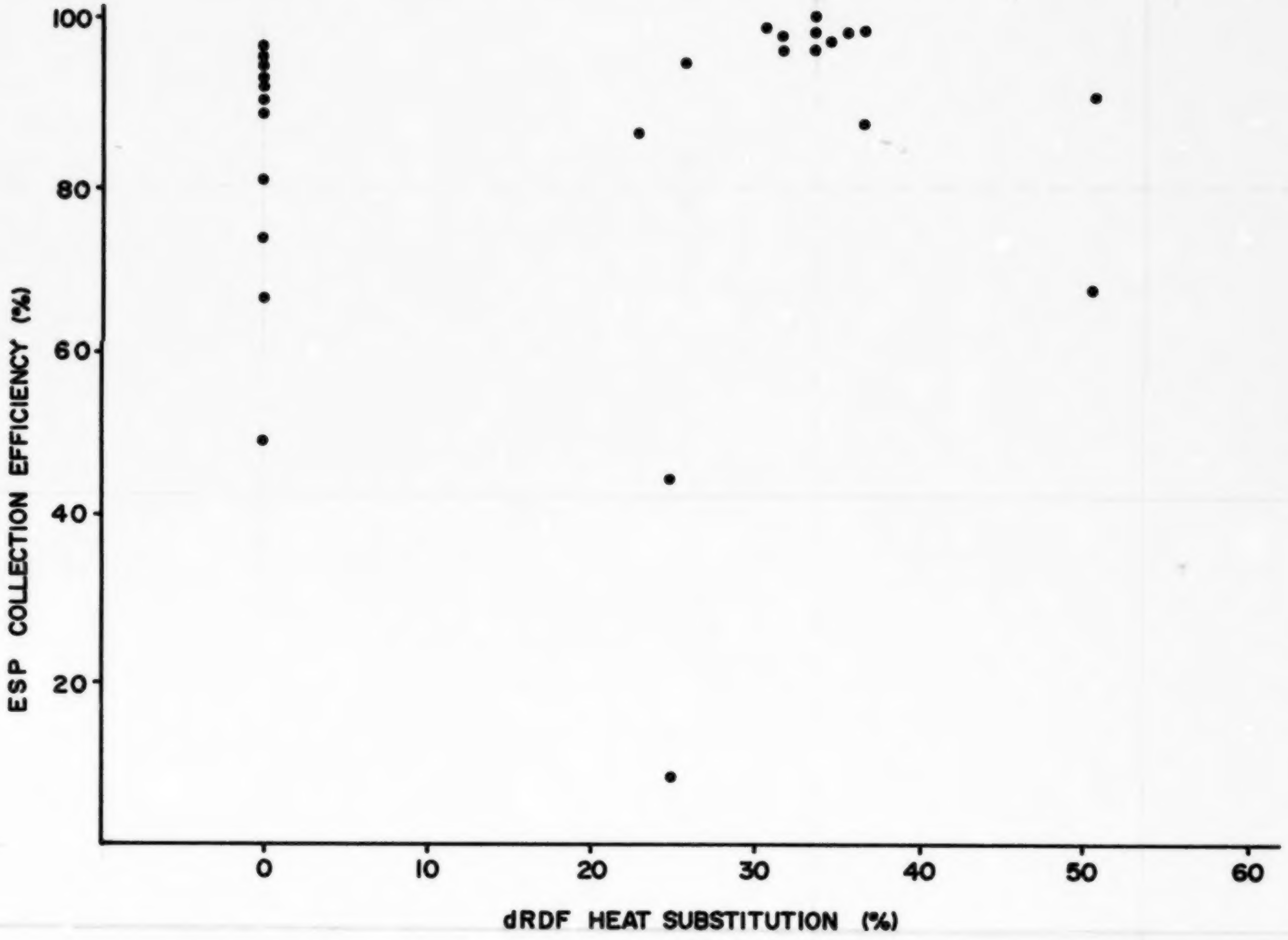

Figure 61. ESP collection efficiency.

Preciptator performance is usually analyzed through use of the Deutch Equation which is expressed as follows:

$$w = \frac{Q}{A} \log_e \frac{1}{P}$$

where

w = drift velocity (ft/min)
Q = volumetric flow rate (ACFM)
A = electrode plate area (ft^2)
$P = \frac{\text{outlet particulate rate}}{\text{inlet particulate rate}}$

This form of the equation expresses the apparent drift velocity of particulate within the precipitator. Drift velocity is a measure of how effectively a precipitator causes particles to migrate toward the collector plates (perpendicular to the gas flow). This measure is commonly used to compare precipitator performance. Factors which could affect drift velocity were analyzed with multiple linear regression analysis, as described later in this report. The results of this statistical analysis show that the drift velocity was not effected by the coal:dRDF blend ratio. The following relationship illustrates the various parameters which do have an influence on drift velocity as determined by statistical analysis of the data.

$$W = 1.49 + .35\ UC + 1.49\ MFG - 2.06S$$

where

W = drift velocity (fpm)
UC = unburnt combustibles in fly ash (percent)
MFG = moisture in flue gas (percent volume)
S = Sulfur content of fuel blend ($lb/10^6$ Btu)

As this relationship demonstrates, precipitator performance was affected by factors influencing the conductivity of the gas stream and the particulates.

Emissions Analysis Techniques

The objective of the tests at G.E. in Erie, Pennsylvania, was to demonstrate that dRDF can successfully be used as a supplementary fuel. Detailed testing was conducted earlier at Maryland Correctional Institute to characterize the technical and environmental aspects of burning dRDF. During the Erie demonstration tests, the evaluations included routine monitoring of air emissions, boiler performance, and the characteristics of the various input and output streams.

Determining the relationships between the individual predictive and response variables measured in a demonstration test of this type is difficult because the predictive variables in a full scale operational system are not as controllable as an experiment usually requires. For example, the properties of both fuels changed from week to week; the condition of the system changed as normal operational and maintenance procedures continued during the tests; and several different boiler operators, each with their own operating techniques were assigned to the unit during the test periods.

These continually changing conditions resulted in such scattered results that they could not be interpreted after simply reducing the field data. In order to better interpret the particulate and gaseous emissions data, the data was normalized to pollutant release rates and then subjected to statistical analysis.

The amount of a pollutant emitted with combustion gases depends primarily upon the concentration of that pollutant in the fuel. Release rate for a pollutant is defined as:

$$\varepsilon = \frac{100 \times \text{measured emission}}{\text{maximum stoichiometrically possible emission}}$$

For example, it is widely accepted that SO_2 emission is proportional to the sulfur content of the fuel. As a general rule, this relationship is true, however the numerous variables which influence the combustion process can cause this relationship to be some function other than direct proportionality.

Release rates were calculated for the following pollutants:

Particulate,

$$\varepsilon_p = \frac{100 \times \text{particulate emission (lb/}10^6\text{ Btu)}}{\text{Fuel ash input (lb/}10^6\text{ Btu)}}$$

SO_x,

$$\varepsilon_{SO_x} = \frac{100 \times SO_2\text{ emissions (lb/}10^6\text{ Btu)}}{2 \times \text{Fuel sulfur content (lb/}10^6\text{ Btu)}}$$

NO_x,

$$\varepsilon_{NO_x} = \frac{100 \times NO_x \text{ emissions (lb/}10^6 \text{ Btu)}}{3.34 \times \text{Fuel nitrogen content (lb/}10^6 \text{ Btu)}}$$

Chlorides,

$$\varepsilon_{Cl} = \frac{100 \times Cl^- \text{ emissions (lb/}10^6 \text{ Btu)}}{\text{Fuel chlorine content (lb/}10^6 \text{ Btu)}}$$

The release rate for particulate emissions as a function of blend substitution ratio is plotted in Figure 62.

The particulate release rate for blends was about the same as for March coal only. But the blends showed a lower release rate than May coal. The high release rates of the May coal were correlated with high unburnt combustibles in the fly ash.

In view of these variables, a common statistical method of extracting correlative information in the data was employed. This method is multiple linear regression analysis. Multiple linear regression analysis assumes that each response variable (e.g., emission levels of pollutants, boiler efficiency, ESP performance, etc.) can be represented as a linear function of the predictive variables (e.g., load, blend, excess air, etc.).

A linear model and a quadratic model were tested for each response variable (Y) of Table 24. The quadratic model failed to produce any more significant combinations of the predictive variables (X_1, X_2, and X_3) than the linear model. Therefore, in all subsequent analyses, only the linear models were applied. To prevent the possibility of invalid correlations due to autocorrelation, the data were tested for possible autocorrelation using the Durban-Watson statistic. Applying autocorrelation corrections to the data failed to produce any significant correlations of the Y's of Table 24 when expressed by the model:

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3$$

Four more X variables were added to account for the type of coal and pellets used in each test. The additional X variables contributed little improvement to the models and added considerable multicolinearity to the data. As a result of these statistical tests, it can be concluded that there is no statistically significant correlation between flue gas emissions and the substitution of dRDF into the fuel. Boiler load and fly ash reinjection also had no significant effect.

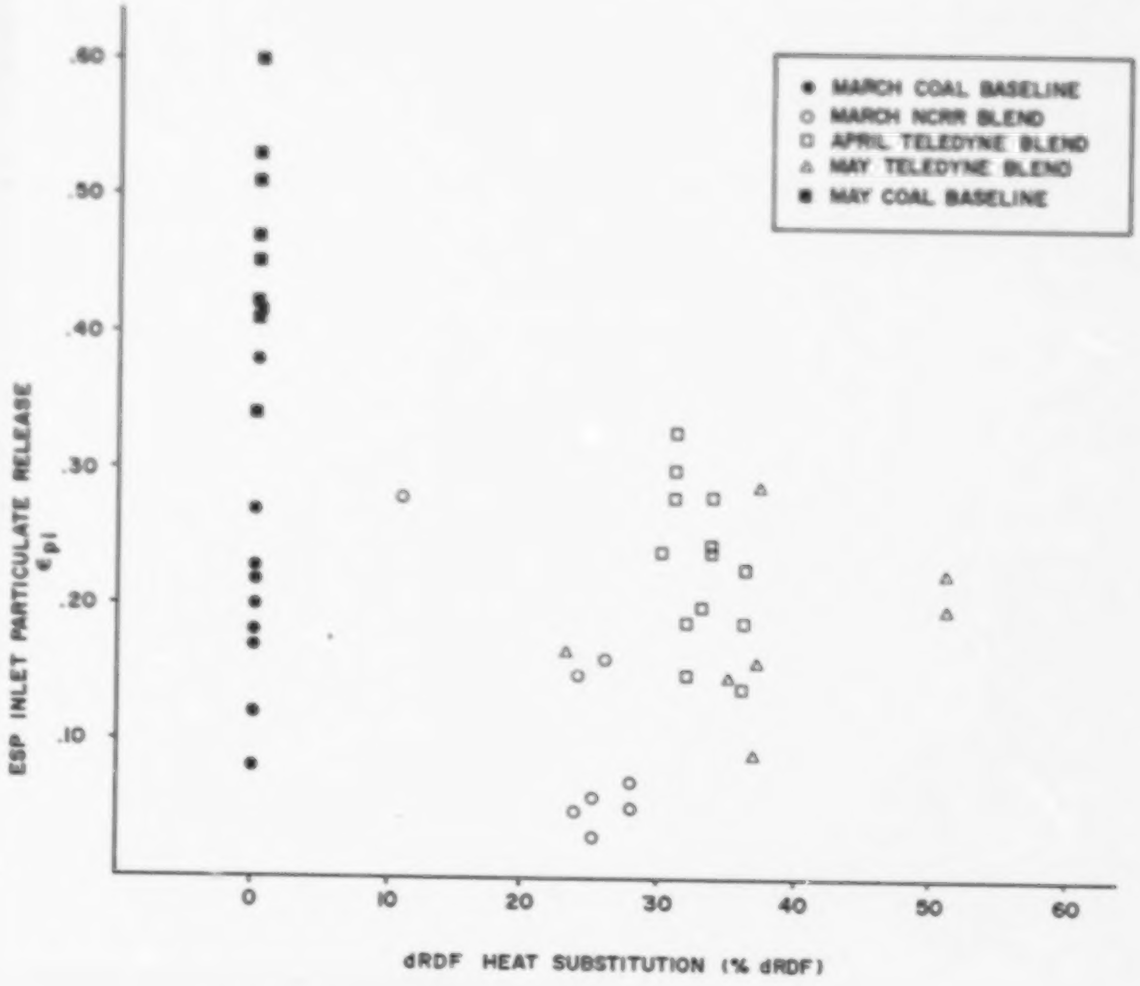

Figure 62. Particulate release rates.

TABLE 24. INITIAL VARIABLE SET

Time Base 1--Method 5 Periods

X_1 = Boiler Load (10^3 lb/hr)
X_2 = Heat Substitution (% dRDF)
X_3 = Fly Ash Reinjection (1 = on, 2 = off)

Y_1 = Particulate Emission ESP Inlet (lb/10^6 Btu)
Y_2 = Particulate Emissions ESP Outlet (lb/10^6 Btu)
Y_3 = NO_x Emission ESP Outlet (lb/10^6 Btu)
Y_4 = SO_x Emission ESP Outlet (lb/10^6 Btu)
Y_5 = CO Flow Rate ESP Outlet (lb/hr)
Y_6 = Chloride Flow Rate ESP Outlet (lb/hr)
Y_7 = Fluoride Flow Rate ESP Outlet (lb/hr)
Y_8 = ESP Power Consumption (kVA)
Y_9 = ESP Efficiency (%)
Y_{10} = Economizer Outlet Opacity (%)

Time Base 2--Efficiency Test Periods

X_1 = Heat Input (10^6 Btu/hr)
X_2 = Heat Substitution (% dRDF)
X_3 = Fly Ash Reinjection (1 = on, 2 = off)

Y_1 = Boiler Efficiency (%)
Y_2 = Fly Ash Output (lb/hr)
Y_3 = Economizer Outlet Temperature (°F)
Y_4 = Dry Flue Gas Output (k - lb/hr)
Y_5 = Moisture Output (lb/hr)
Y_6 = Bottom Ash Losses (%)
Y_7 = Fly Ash Losses (%)
Y_8 = Dry Flue Gas Losses (%)
Y_9 = Wet Flue Gas Losses (%)

In an effort to find which predictive variables did effect emissions, the functional relationships expressed in Table 25 and Table 26 were selected as typical for a combustion system of the type tested. The emissions have been converted to release rates to normalize the effect of fuel type.

A stepwise linear regression analysis was performed on each Y variable of Table 25 to screen out which X variables had a measurable influence on each Y. The data analyzed is included in Table 27. It was found that the pellet type identification variables (X_9 and X_{10}) had no significant influence but added considerable multicolinearity to the X variable matrix. The pellet identification variables were therefore dropped, and the stepwise linear regression analysis was rerun.

TABLE 25. VARIABLE EXPECTED TO HAVE FUNCTIONAL RELATIONSHIPS

Response variables	Predictive variables										
	X_1 ℓ	X_2 γ	X_3 Rei	X_4 EA	X_5 Cf	X_6 Pf	X_7 UC	X_8 M_{fg}	X_9 (dRDF-Type)	X_{10}	X_{11} S
Y_1 ϵ_{pi}	*	*	*	*	*	*	*		*	*	
Y_2 ϵ_{po}	*	*	*	*	*	*	*	*	*	*	*
Y_3 ϵ_{NO_x}	*	*	*	*	*	*			*	*	
Y_4 ϵ_{SO_x}	*	*	*	*					*	*	*
Y_5 ϵ_{Cl}	*	*	*	*					*	*	
Y_6 ω	*	*	*	*	*	*	*	*	*	*	*
Y_7 B	*	*	*	*	*	*	*		*	*	
Y_8 η	*	*	*	*	*	*	*		*	*	

$$Y = b_o + b_1x_2 + b_2x_2 + b_3x_3 + \ldots . b_nx_n$$

TABLE 26. DEFINITIONS OF VARIABLES AND SYMBOLS FOR TABLE 25

Response Variables

Y_1 = ε_{pi} = Particulate release rate at ESP inlet (%)

Y_2 = ε_{po} = Particulate release rate at ESP outlet (%)

Y_3 = ε_{NO_x} = NO_x release rate at ESP outlet (%)

Y_4 = ε_{SO_x} = SO_x release rate at ESP outlet (%)

Y_5 = ε_{Cl} = Chloride release rate at ESP inlet (%)

Y_6 = ω = ESP drift velocity (fpm)

Y_7 = B = Particulate characteristic size at inlet (μm)

Y_8 = η = Particulate size uniformity (Wiebull Slope)

Predictive Variables

X_1 = ℓ = Boiler load (% capacity)

X_2 = γ = Blend (% of input Btu's from dRDF)

X_3 = Rei = Fly ash reinjection (on or off)

X_4 = EA = Excess air (%)

X_5 = Cf = Coal fines (% < 3/8 in.)

X_6 = Pf = Pellet fines (% < 3/8 in.)

X_7 = UC = Unburnt carbon in fly ash (%)

X_8 = M_{fg} = Moisture in flue gas (% by volume)

X_9 =

Dummy variables expressing dRDF type

X_{10} =

X_{11} = S = Total sulfur input (lb/10^6 Btu)

TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS

Date	ϵ_{pi} (Y_1)	ϵ_{po} (Y_2)	E_{NO_x} (Y_3)	E_{SO_x} (Y_4)	ϵ_{Cl} (Y_5)	W (Y_6)	D_{67} (Y_7)	n (Y_8)
3-5 AM	22		100	10	15		18	.65
3-5 PM	--		--	12	15		29	1.05
3-6 AM	18		--	108	37		10	.47
3-6 PM	20		--	124	34		38	.68
3-7 AM	12		58	126	29		45	.74
3-7 PM	27		--	103	78		29	.83
3-8 AM	17	5.5	53	65	24	4.7	52	.64
3-8 PM	38	2.4	51	88	66	11.9	75	.54
3-9 AM	22	4.1	53	51	34	7.5	16	.80
3-9 PM	8	4.2	61	78	8	3.1	90	.49
3-13 AM	7		10	36	22		20	--
3-13 PM	11		7	49	132		46	.47
3-14 AM	5		10	41	37		27	.75
3-14 PM	15		15	57	92		46	.43
3-15 AM	5		25	53	22		16	.62
3-15 PM	16	0.6	21	74	59	15.2	46	.68
3-16 AM	3	2.7	16	45	12	.38	18	.64
3-16 PM	6	3.4	14	36	40	2.5	19	.55
4-18 AM	24		16	42	123		67	.56
4-18 PM	20		14	90	93		210	.77
4-19 AM	28	0.3	15	69	108	19.2	32	.68
4-19 PM	24	0.2	15	66	102	19.6	85	.62
4-20 AM	24	0.3	17	65	111	19.4	14	.82
4-20 PM	30	0.3	15	72	101	20.6	16	.76
4-21 AM	28		18	161	104		26	.76
4-21 PM	33		26	129	121		--	--
4-23 AM	19		13	59	86		67	.54
4-23 PM	23		16	74	100		24	.90
4-24 AM	14	0.2	18	--	116	17.3	25	.67
4-24 PM	19	0.2	18	--	1	22.2	60	.80
4-25 AM	15	0.3	13	54	1	15.1	100	.63
5-7 PM	9	--	14	66	91	--	13	.74
5-8 AM	16	1.2	19	49	56	10.3	87	.53
5-8 PM	--	0.8	17	78	99	--	6	.52
5-9 AM	--	--	15	77	100	--	70	.46
5-9 PM	15	0.5	15	78	77	17.3	70	.60
5-10 AM	29	0.7	19	47	110	15.8	63	.88
5-10 PM	17	2.1	14	78	113	9.8	80	.75
5-11 AM	23	7.8	19	67	95	5.0	68	.47
5-11 PM	20	2.4	14	50	97	10.0	64	.63
5-14 AM	--	--	--	--	--	--	--	--
5-14 PM	41	--	22	63	157	--	9.5	.54

(continued)

TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS (continued)

Date	ϵ_{pi} (Y_1)	ϵ_{po} (Y_2)	E_{NO_x} (Y_3)	E_{SO_x} (Y_4)	ϵ_{Cl} (Y_5)	W (Y_6)	D_{67} (Y_7)	n (Y_8)
5-15 AM	47	--	18	71	118	--	70	.45
5-15 PM	53	--	17	82	110	--	47	.84
5-16 AM	51	2.2	21	54	47	15.3	58	.77
5-16 PM	60	2.4	--	50	145	16.8	29	.76
5-17 AM	45	1.9	18	33	76	15.4	39	.67
5-17 PM	42	2.0	19	33	112	14.8	40	.70
5-18 AM	42	1.8	20	38	115	14.2	101	.79
5-18 PM	34	1.7	--	50	127	14.7	17.4	.76

(continued)

TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS (continued)

Date	Boiler load % capacity (X_1)	Heat blend (% dRDF) (X_2)	Fly ash reinj. (X_3)	Excess air (%) (X_4)	% weight coal fines (X_5)	% weight pellet fines (X_6)
3-5 AM	50	0	0	96	68	0
3-5 PM	48	0	0	164	68	0
3-6 AM	42	0	0	148	67	0
3-6 PM	43	0	0	179	84	0
3-7 AM	76	0	0	101	84	0
3-7 PM	76	0	0	126	84	0
3-8 AM	96	0	0	64	84	0
3-8 PM	95	0	0	70	84	0
3-9 AM	94	0	0	73	82	0
3-9 PM	96	0	0	84	82	0
3-13 AM	66	28	0	94	30	54
3-13 PM	73	28	0	85	30	54
3-14 AM	66	28	0	103	56	52
3-14 PM	71	24	0	98	56	52
3-15 AM	76	24	0	109	44	39
3-15 PM	89	26	0	99	43	39
3-16 AM	81	25	0	105	39	41
3-16 PM	82	25	0	103	39	41
4-18 AM	76	30	0	105	50	10
4-18 PM	77	33	0	98	50	10
4-19 AM	87	34	0	86	57	20
4-19 PM	83	34	0	83	57	20
4-20 AM	80	34	0	108	59	33
4-20 PM	91	31	0	90	59	33
4-21 AM	40	31	0	319	39	22
4-21 PM	31	31	0	354	39	22
4-23 AM	55	36	0	106	48	20
4-23 PM	96	36	0	86	48	20
4-24 AM	80	37	1	100	58	42
4-24 PM	96	32	1	94	58	42
4-25 AM	83	32	1	79	47	48
5-7 PM	40	37	0	142	36	27
5-8 AM	95	37	0	112	62	24
5-8 PM	99	35	0	92	62	24
5-9 AM	83	35	1	90	41	34
5-9 PM	103	35	0	92	41	34
5-10 AM	86	37	0	89	39	25
5-10 PM	99	23	0	81	39	25
5-11 AM	95	51	0	83	64	30
5-11 PM	92	51	0	93	64	30
5-14 AM	76	51	0	--	--	0
5-14 PM	46	0	0	259	--	0

(continued)

TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS (continued)

Date	Boiler load % capacity (X_1)	Heat blend (% dRDF) (X_2)	Fly ash reinj. (X_3)	Excess air (%) (X_4)	% weight coal fines (X_5)	% weight pellet fines (X_6)
5-15 AM	72	0	0	120	65	0
5-15 PM	70	0	0	136	65	0
5-16 AM	92	0	0	109	63	0
5-16 PM	96	0	0	112	63	0
5-17 AM	93	0	0	97	58	0
5-17 PM	95	0	0	95	58	0
5-18 AM	96	0	1	82	62	0
5-18 PM	94	0	1	97	62	0

(continued)

TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS (continued)

Date	Fly ash carbon (% wt.) (X_7)	Flue gas moisture (X_8)	Pellet (X_9)	Type (X_{10})	Fuel sulfur (lb/10^6 Btu) (X_{11})
3-5 AM	36	4.1	0	0	3.37
3-5 PM	36	4.1	0	0	3.37
3-6 AM	26	3.9	0	0	3.37
3-6 PM	26	3.9	0	0	3.37
3-7 AM	27	4.5	0	0	3.37
3-7 PM	27	4.5	0	0	3.37
3-8 AM	25	5.8	0	0	3.37
3-8 PM	25	5.8	0	0	3.37
3-9 AM	24	5.3	0	0	3.37
3-9 PM	24	5.3	0	0	3.37
3-13 AM	22	7.0	1	0	4.36
3-13 PM	22	7.0	1	0	4.30
3-14 AM	21	7.0	1	0	4.30
3-14 PM	21	6.2	1	0	4.45
3-15 AM	20	6.2	1	0	4.45
3-15 PM	20	5.6	1	0	4.44
3-16 AM	19	7.2	1	0	4.45
3-16 PM	19	7.2	1	0	4.45
4-18 AM	24	8.2	1	1	1.39
4-18 PM	24	8.4	1	1	1.33
4-19 AM	24	8.6	1	1	1.36
4-19 PM	24	8.6	1	1	1.36
4-20 AM	23	8.6	1	1	1.36
4-20 PM	23	8.4	1	1	1.38
4-21 AM	22	7.4	1	1	1.36
4-21 PM	22	7.4	1	1	1.36
4-23 AM	27	5.8	1	1	1.33
4-23 PM	27	5.8	1	1	1.33
4-24 AM	23	5.8	1	1	1.33
4-24 PM	23	7.9	1	1	1.37
4-25 AM	21	7.9	1	1	1.37
5-7 PM	39	5.3	1	1	.96
5-8 AM	26	5.3	1	1	.96
5-8 PM	26	6.8	1	1	.97
5-9 AM	21	7.5	1	1	.97
5-9 PM	21	7.5	1	1	.97
5-10 AM	23	6.1	1	1	.95
5-10 PM	23	5.4	1	1	1.10
5-11 AM	11	8.6	1	1	.80
5-11 PM	11	8.6	1	1	.80
5-14 AM	30	8.6	0	0	.80
5-14 PM	30	3.9	0	0	1.57

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TABLE 27. FINAL DATA USED IN STATISTICAL ANALYSIS (concluded)

Date	Fly ash carbon (% wt.) (X_7)	Flue gas moisture (X_8)	Pellet (X_9)	Type (X_{10})	Fuel sulfur (lb/10^6 Btu) (X_{11})
5-15 AM	28	4.8	0	0	1.57
5-15 PM	28	4.8	0	0	1.57
5-16 AM	40	4.5	0	0	1.57
5-16 PM	40	4.4	0	0	1.57
5-17 AM	43	4.3	0	0	1.57
5-17 PM	43	5.0	0	0	1.57
5-18 AM	34	4.6	0	0	1.57
5-18 PM	34	4.6	0	0	1.57

The variable sets showing significance in the stepwise analysis were then analyzed in a multiple linear regression and tested for autocorrelation. The variables showing no autocorrelation were subjected to a ridge regression analysis. The data sets having autocorrelation were transformed by iterative application Cochran-Orcutt Method. This transformed data was then analyzed by ridge regression.

Ridge regression analysis was performed because a low to moderate amount of multicolinearity existed in the X variable matrix, and ridge regression analysis does not require an orthogonal data set.

In the resulting linear models presented below, only those independent variables having a significant "t" value after the ridge regression analysis were included in the model. Final results of the statistical analysis are included in Tables 28 and 29.

TABLE 28. FINAL RESULTS OF STATISTICAL ANALYSIS

Correlation coefficient	At 90% confidence level ($\alpha = .10$)
$r^2 = .33$	$E_{pi} = .01\ A_I\ (-10.81 + .214\ell + .075\ EA + .266\ Pf + .533\ UC)$
$r^2 = .11$	$E_{po} = .01\ A_I\ (-1.183 + .051\ Cf)$*
$r^2 = .39$	$E_{po} = .01\ A_I\ (5.918 - .0576\ Pf - .1096\ UC)$*
$r^2 = .47$	$E_{NO_x} = .0343\ A_N\ (1.473 - .2025\gamma + .4234\ Cf)$
$r^2 = .24$	$E_{SO_x} = .02\ A_s\ (41.39 + .229\ EA)$
$r^2 = .45$	$\omega = -1.49 + .35\ UC + 1.49\ M_{fg} - 2.06\ S$
$r^2 = .11$	$B = 47.967 + .441\gamma - .404\ Pf$
$r^2 = .12$	$n = .4964 + .0067\ UC$

NOTE: No significant correlations were found for chloride and carbon monoxide emissions.

* The stepwise regression indicated that two models described the emissions of particulate at the ESP outlet.

TABLE 29. DEFINITIONS OF TERMS USED IN FINAL RESULTS OF STATISTICAL ANALYSIS

A_I = Ash content of the blended fuel (lb/10^6 Btu)

A_N = Nitrogen content of the blended fuel (lb/10^6 Btu)

A_S = Sulfur content of the blended fuel (lb/10^6 Btu)

B = $D_{63.21}$ of the particle size distribution at the ESP inlet (μm)

Cf = Coal fines (percent by weight <3/8 in.)

EA = Excess air level (percent)

E_{NO_x} = NO_x emission rate (lb/10^6 Btu)

E_{pi} = Particulate rate at ESP inlet (lb/10^6 Btu)

E_{po} = Particulate emissions at ESP outlet (lb/10^6 Btu)

E_{SO_x} = SO_x emission rate ESP outlet (lb/10^6 Btu)

ℓ = Boiler load (percent maximum rated capacity)

M_{fg} = Flue gas moisture level (percent by volume)

n = Slope of Wiebull plot for ESP inlet particulate (Roslin-Rammler exponent)

Pf = dRDF fines (percent by weight <3/8 in.)

S = Sulfur content of the fuel blend (lb/10^6 Btu)

UC = Unburnt combustables in fly ash (percent of fly ash weight)

ω = Drift velocity of ESP (fpm)

γ = dRDF substitution rate (percent Btu input from dRDF)

It should be noted that when no functional relationships were found it could mean either the functional relationship does not exist or the experiment was not designed to adequately test for that relationship.

Gaseous Emissions

As Figure 63 indicates, sulfur release was not changed by the substitution of dRDF in the fuel. The March coal only data points showing release rates in excess of 100 percent were the result of using the average weekly coal analyses to determine the input sulfur rate. On an hourly basis, actual variability in sulfur content could exceed 25 percent of the measured value.

Statistical analysis of the SO_2 concentrations measured in the flue gas show that SO_x emissions are proportional to the sulfur input rate. No secondary effects were measured. Since dRDF is a low sulfur fuel, increasing dRDF substitutions cause decreasing sulfur emissions.

Gaseous SO_2 emissions at the precipitator outlet as measured by electrochemical cell are plotted in Figure 64. It was not possible to conduct all the tests using the same coal. A range of sulfur contents from 1.7 percent to 6.8 percent was found in the five different coal types identified. This wide range of sulfur input rates correspondingly resulted in a wide range of SO_2 emissions. The decreasing SO_2 emission rate with increasing dRDF increasing substitution can be observed on Figure 64. The NCRR pellets and Teledyne pellets had sulfur contents of .43 percent and .23 percent, respectively (see Table 30). On a sulfur content per unit heating value basis, these dRDF fuels have a sulfur content corresponding to coal having .76 percent and .34 percent sulfur, respectively.

The combustion of dRDF blends emitted generally less NO_x than did the combustion of coal only. This is probably caused by the low nitrogen content of dRDF. On a per unit heat input basis, Teledyne pellets had about half the nitrogen content of coal, and NCRR pellets had about 90 percent of the nitrogen content of coal (see Table 30).

Figure 65 shows a plot of the NO_x emissions as a function of dRDF substitution. The high NO_x levels reported for March coal only firing are extremely high for coal combustion and could be the result of some undetermined error in the data. However, these results have been included in the statistical analysis as reported here. Upon comparing all blend firing results to the May coal baseline results in Figure 65, it can be observed that dRDF blends emitted about the same to slightly less NO_x than the May coal.

The statistical analysis showed that firing dRDF reduces the NO_x release rate, but from Figure 66 it can be observed that this may be a false interpretation. This reduction appears to result from the high NO_x of March coal baseline which itself is correlated with a high fines content in that coal.

Chloride and fluoride emissions were analyzed using specific ion electrodes in the impinger catches of the Method 5 particulate tests. This method accounts for the chloride and fluoride ions found in the flue gas in the gaseous phase. Chloride concentrations in the fly ash and bottom ash were investigated by Northrop Services, Inc., under Contract 68-02-2566 with EPA Environmental Sciences Research Laboratory at Research Triangle Park,

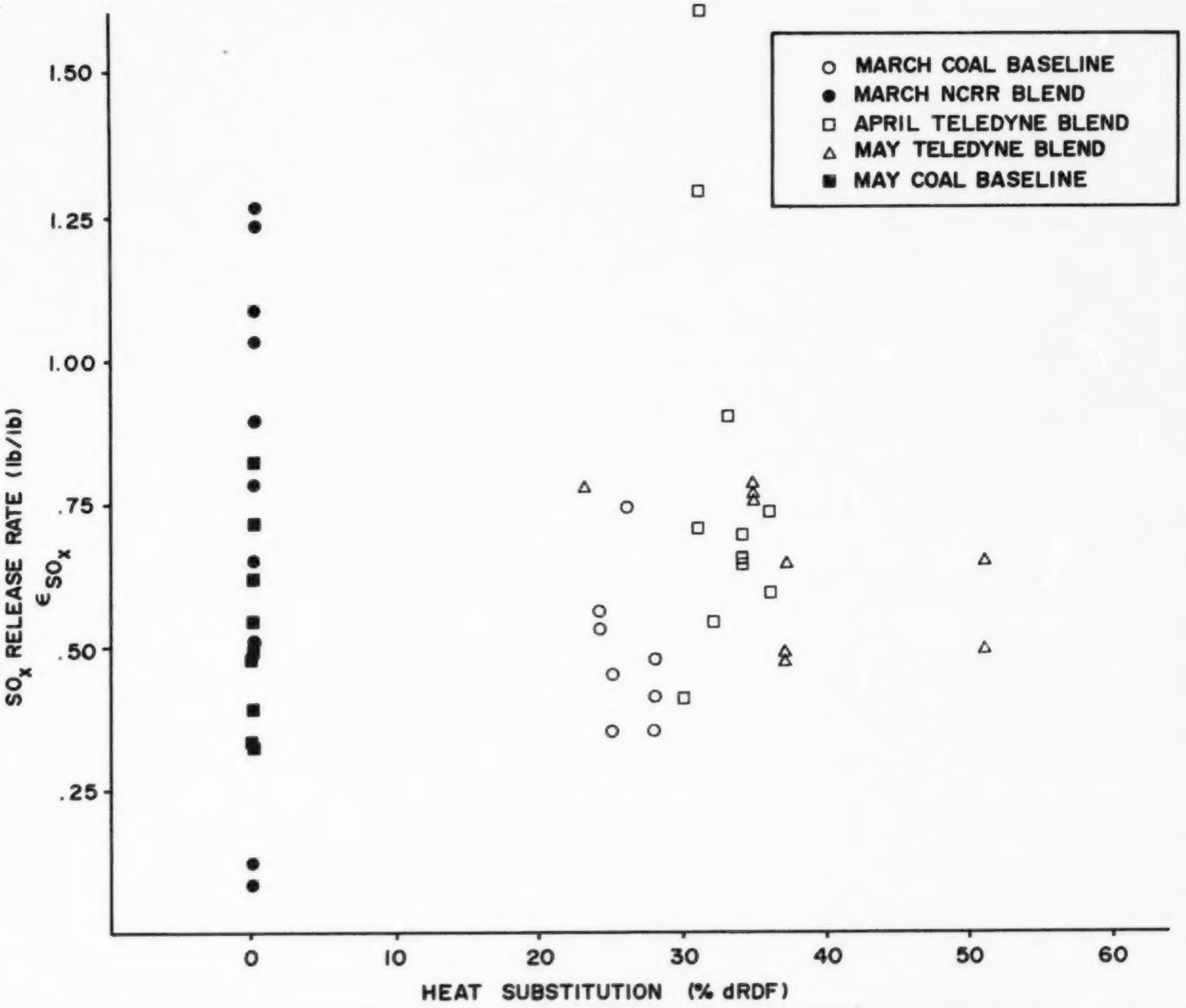


Figure 63. SO_x release rate.

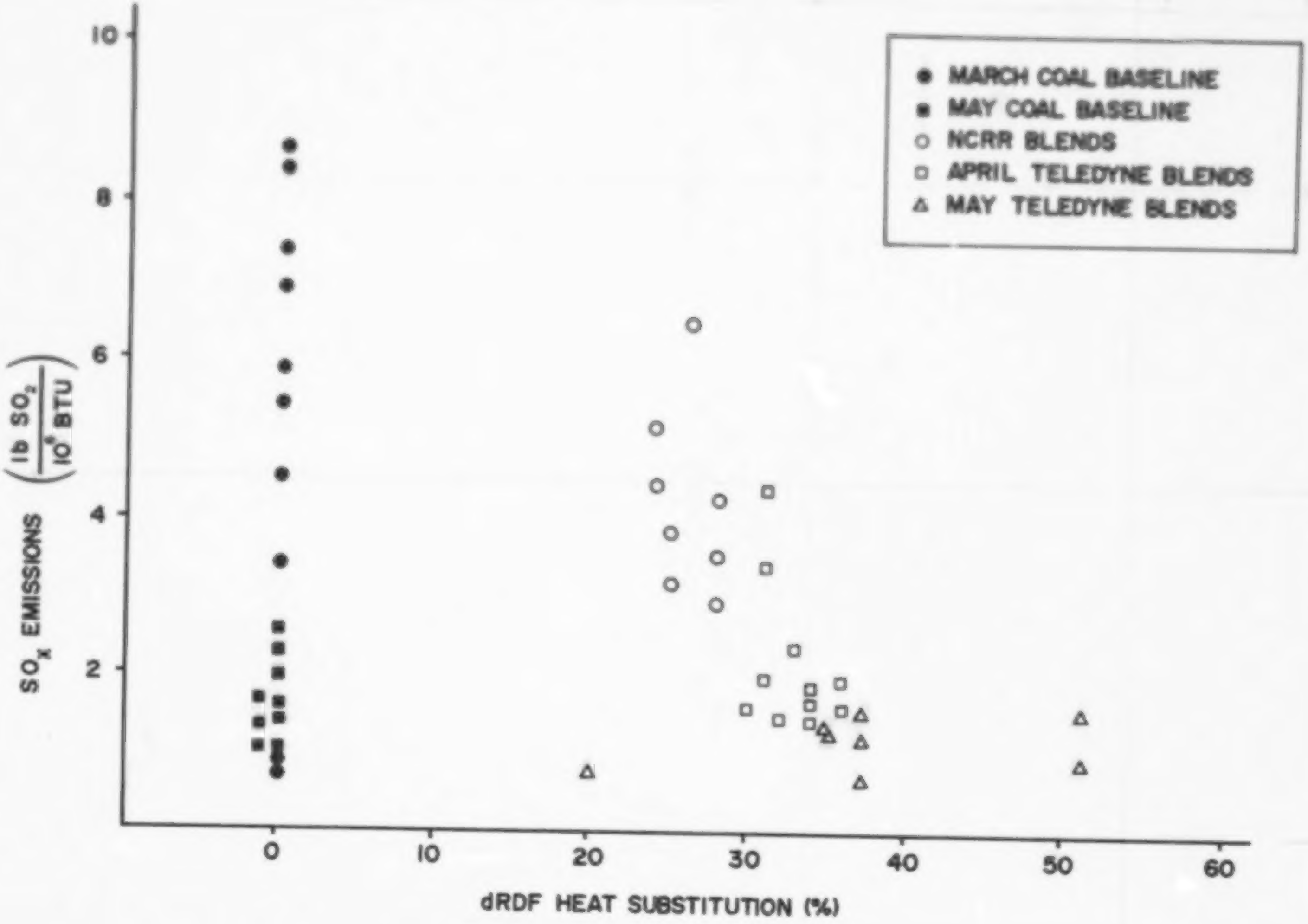


Figure 64. SO_x emissions.

TABLE 30. FUEL POLLUTANT LEVELS*

Dates	Fuel	Inerts ($lb/10^6$ Btu)	Sulfur ($lb/10^6$ Btu)	Nitrogen ($lb/10^6$ Btu)
3/5 - 3/9	Coal A	12.65	3.37	.86
3/12 - 3/16	Coal B	15.36	5.71	.86
4/18 - 4/25	Coal C	10.30	1.76	.97
5/7 - 5/11	Coal D	7.39	1.35	.99
5/14 - 5/18	Coal E	7.57	1.57	.94
3/12 - 3/16	NCRR pellets	45.52	0.64	.87
4/18 - 5/11	Teledyne pellets	17.03	0.28	.45

* Based on fuel heating value.

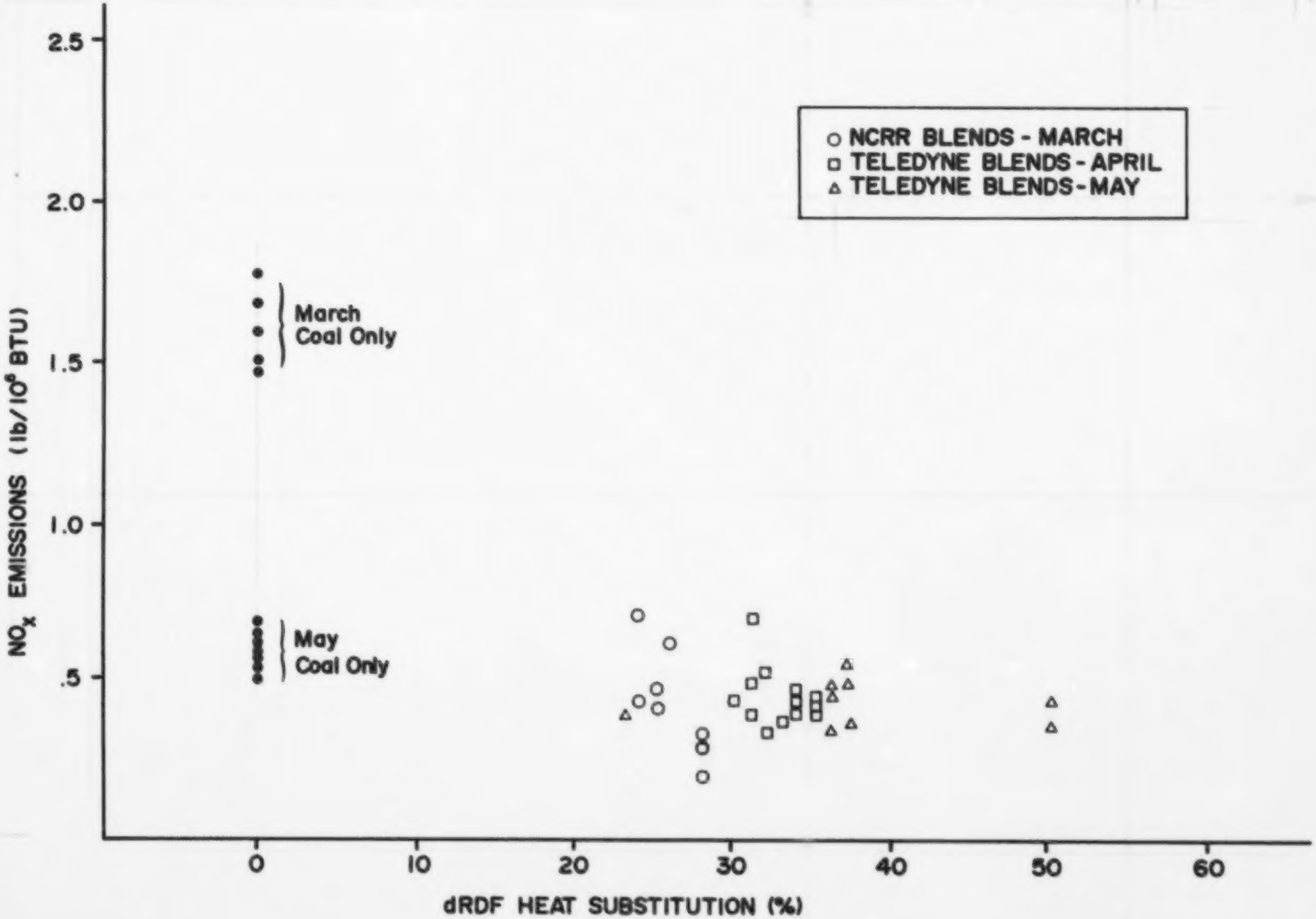


Figure 65. NO_x emissions.

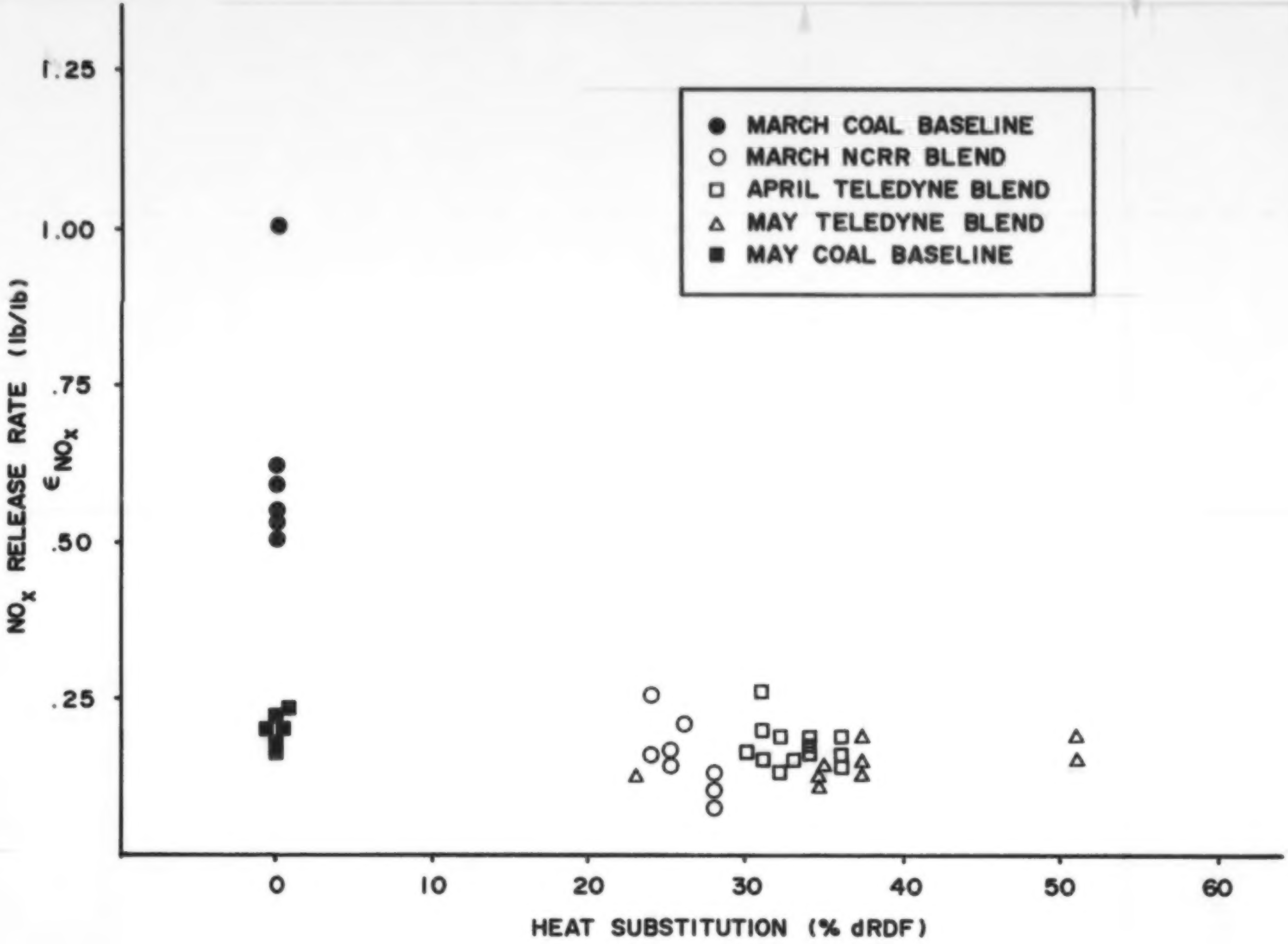


Figure 66. NO$_X$ release rate vs. heat substitution.

North Carolina. Results of this study can be found in the Northrop Report No. ES-TR-79-33, published in October 1979.

Coal used in these tests had a chlorine content of .12 percent to .16 percent, while the NCRR pellets and Teledyne pellets had chlorine contents of .31 percent and .38 percent, respectively. On a heat input basis, the coal contained .11 to .12 lb/10^6 Btu chlorine while dRDF contained approximately .46 lb/10^6 Btu chlorine. Since dRDF firing introduces chlorine at a higher rate than coal, an increase in chloride emissions was anticipated. As expected, chloride emissions did increase, as can be observed on Figure 67. It can be noted that a few of the chloride emission rates exceeded the chlorine input rate. This discrepancy indicates the lack of precision in the analytical technique for chloride emissions measurement.

On the average, chloride emissions were proportional to the chlorine input rate. No second order effects which would limit the amount of input chlorine released were measured. Actual chloride concentrations at the ESP inlet ranged from 10 ppm to 95 ppm for coal only firing and 5 ppm to 213 ppm for coal and dRDF blend firing. Relevant chlorine results are tabulated in data columns 11, 20B, 24, 25, 40, 91, 111, and 272 of Appendix B.

Maximum fluoride concentration measured while burning coal only or dRDF/coal blends was 7.5 ppm. Therefore all fluoride concentrations were near the detection limit of the analytical technique and are well below the levels necessary to cause any environmental or operational concern.

The data in Figure 68 indicated that some reaction occurred in the March coal baseline and NCRR blend firings which prevented total release of the chlorine into the flue gas. However, the variable affecting this inhibition cannot be identified by statistical analysis of the independent variables.

Carbon monoxide levels were consistently low for both coal only and dRDF blend firing. Statistically there was no difference detected between the CO emissions of coal only firing and dRDF blend firing. As Figure 69 indicates, excess air had no effect on CO emissions except for a few dRDF blend firing tests. As can be seen in Figure 70, carbon monoxide emissions appear to be higher for dRDF firing than for coal only at higher boiler loads. At low load, stable operation is difficult to achieve, and the observed CO emission effects cannot be inferred to result from dRDF substitution effects. These higher CO emissions seen at high load are probably due to the overfire/underfire air balance. Before commencing the demonstration the boiler was tuned for optimum combustion of coal. Since dRDF is a more volatile fuel than coal, the overfire air should have been increased for blend firing. But the overfire/underfire balance was left unchanged because fusion temperatures of the fuel blends were still unknown, and the higher relative amount of underfire air reduced the probability of clinkering problems by cooling the fuel bed. More overfire air would have increased the mixing and thus reduced carbon monoxide concentrations. This effect is more pronounced at higher loads where heat release rates are high and retention times short. At these higher loads any perturbation in the operation, such as

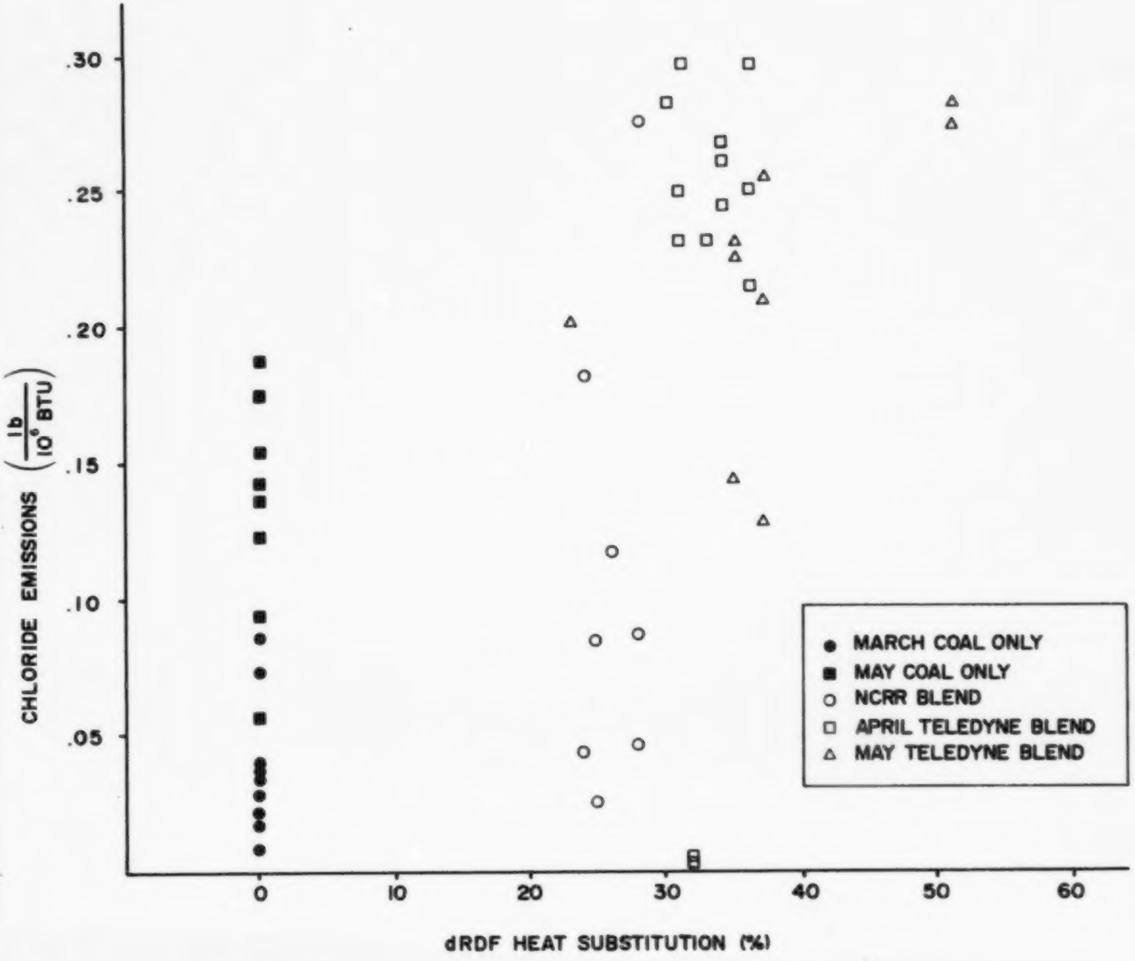


Figure 67. Chloride emissions vs. dRDF heat substitution.

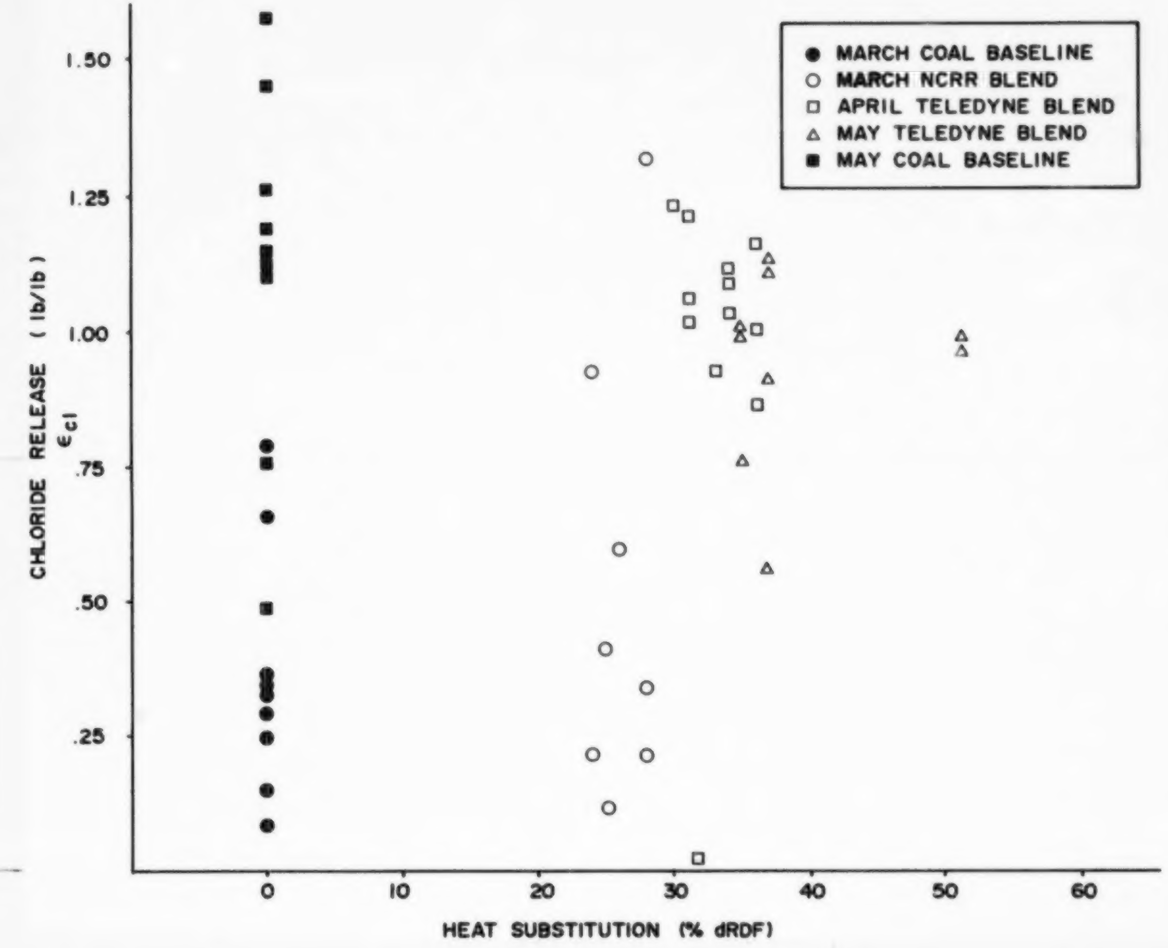


Figure 68. Chloride release vs. heat substitution.

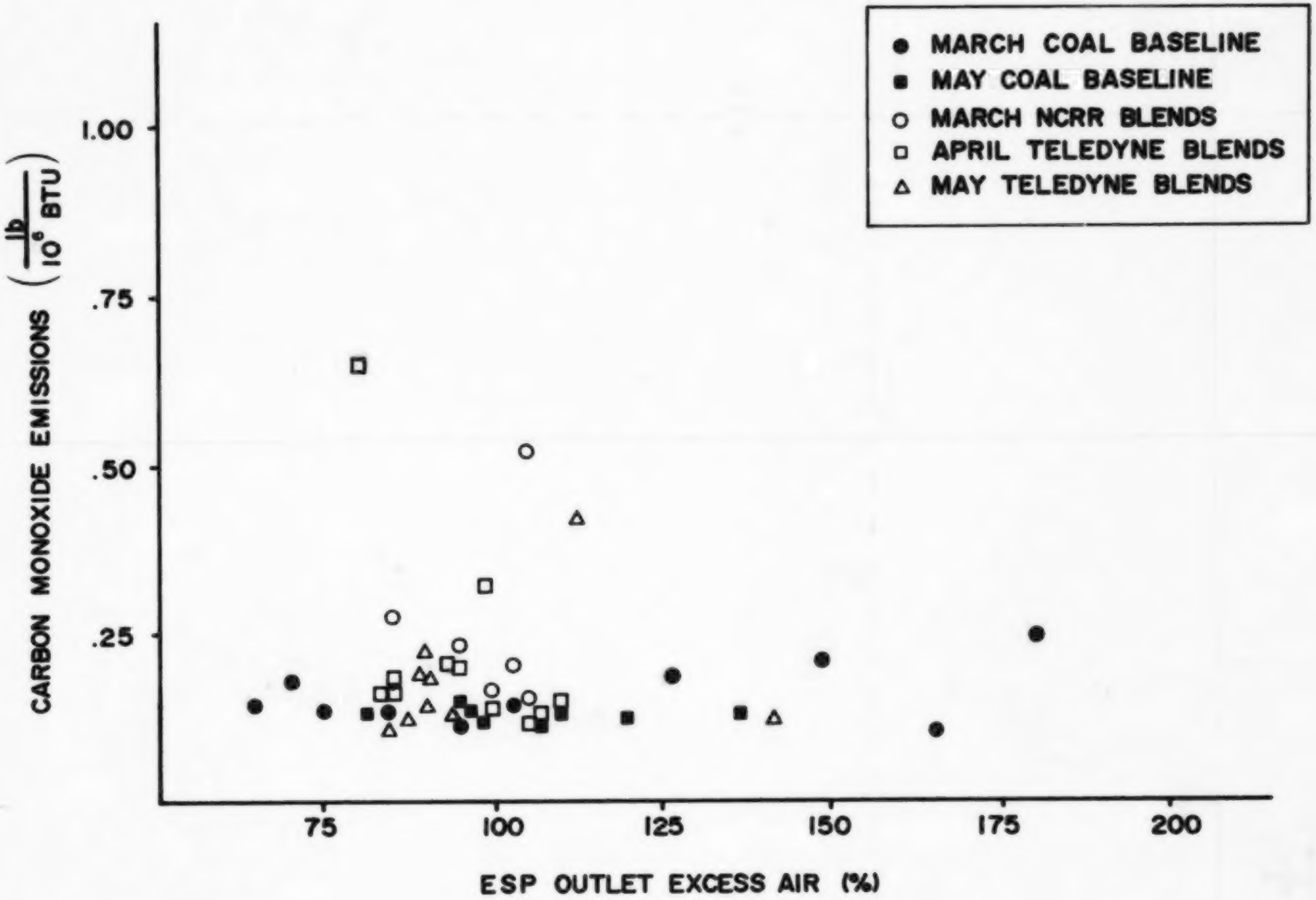
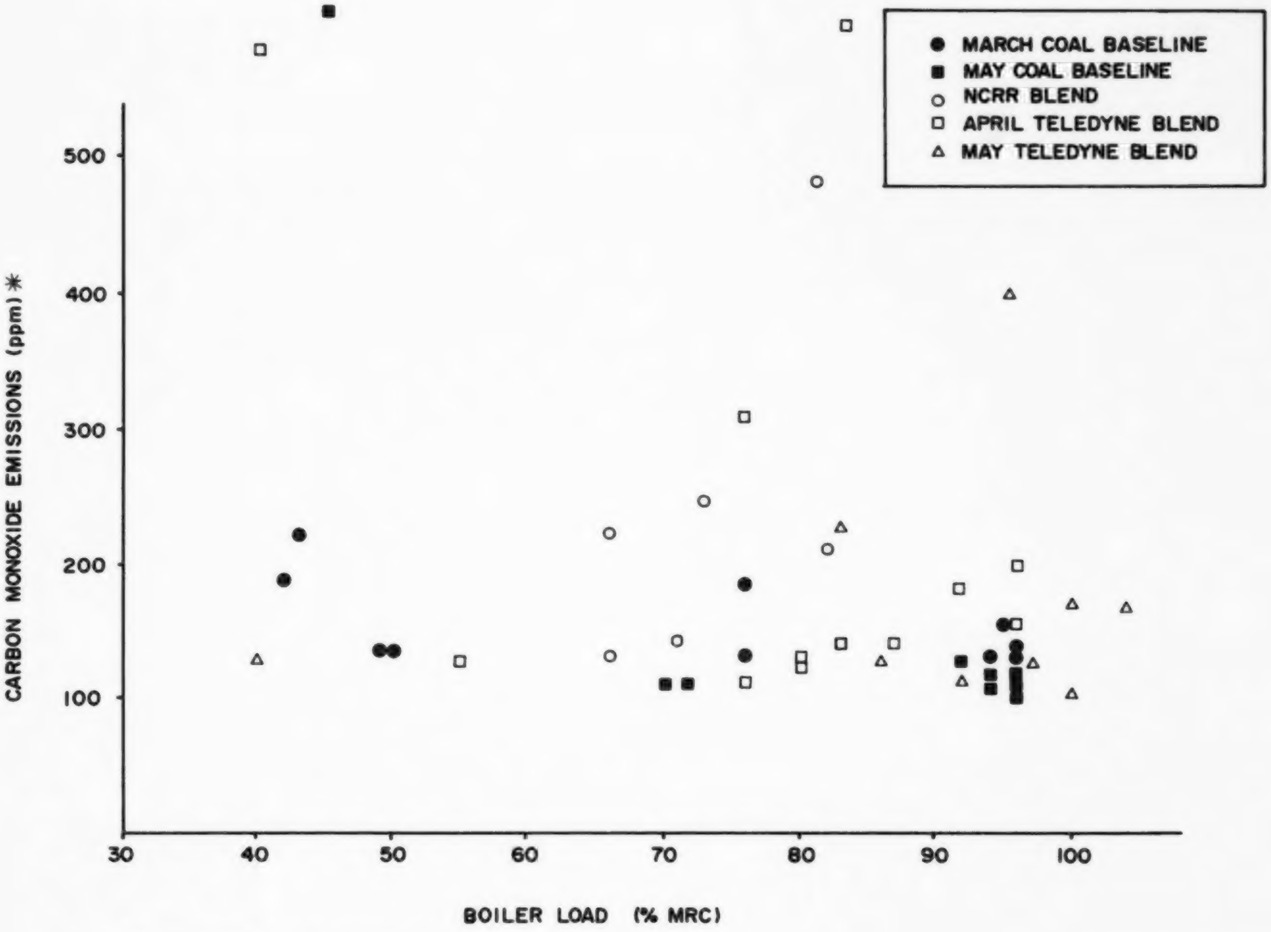


Figure 69. Carbon monoxide emissions vs. ESP outlet excess air.



* CORRECTED TO 50% EXCESS AIR

Figure 70. Carbon monoxide emissions vs. boiler load.

an increase in fuel moisture or swings in boiler load, can increase the need for mixing to achieve combustion of carbon monoxide.

Unburnt hydrocarbons were measured by gas chromatography using a flame ionization detector. All measurements made for coal only and coal/dRDF blend firings indicated concentrations of less than 10 ppm, which is the minimum detection level for the instrument. At this concentration it can be concluded that no significant levels of hydrocarbons were emitted.

The combustion gases were analyzed for phosgene content at the boiler outlet with a National Dräger multigas detector using phosgene detection tubes. The detection tubes used had a minimum detection level of .25 ppm. No phosgene was detected even after passing five times the prescribed gas volume through the detection tube.